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Phase-based Planning for Railway Infrastructure Projects

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Phase-based Planning for Railway Infrastructure Projects

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Finally, I would like to thank my friends for being around during this whole endeavor. Most of all, thanks to my wife and my two lovely daughters for their unselfish love and support.

PREFACE

This thesis was carried out at Technical University of Denmark (DTU) and submitted to the Management Science division, DTU Management Engineering. Prof. Allan Larsen was the principle supervisor of the Ph.D. student, while Associate Prof. (previous) Kim Bang Salling and Associate Prof. (previous) Alex Landex and Railway Section Leader Steen Nørbæk Madsen from Rambøll Denmark acted as co-supervisors.

The title of the thesis is "Phase-based Planning for Railway Infrastructure Projects". The thesis is based on three academic papers and two conference papers. Two academic papers have been published in international peer-reviewed journals which are ISI-indexed. The third academic paper is under review. The two conference papers are published/presented in a national peer-reviewed conference (Trafikdage 2013). All papers are co-authored.

The thesis consists of seven chapters. The first six chapters (1-6) are the introduction to the included papers which are attached after chapter (6). In the introduction chapters, the first two chapters (1, 2) introduce railway infrastructure, present railway planning problems and the current planning challenges in real practices in Denmark. Following chapter (3) explains the concept of phase-based decision support system and illustrates the application of proposed Operations Research (O.R.) optimization models to solve the current planning challenges. Finally, the next three chapters (4-6) discuss the pros and cons for different railway maintenance planning strategies, highlight the contributions of the thesis, and conclude the main findings.

The project was funded by the Danish Railway Sector Association (BaneBranchen). The Ph.D. studies were conducted between January 15th, 2013 and April 20th, 2017.

SUMMARY

Maintenance for railway infrastructure is expensive and it often connects to a large cost investment. The maintenance work, which is implemented in track possessions, can also cause inconvenience to train operators and passengers. Therefore, Planning for maintenance and track possession is important in terms of economy and rail operations.

This study presents two types of Phase-based Decision Support System (PDSS), i.e. Functional Phase-Based Planning Approach (F-PBPA) and Process-Oriented Phase-Based Planning Approach (PO-PBPA). They are used for decision support for the planning of the railway infrastructure maintenance activities at the strategic planning level. The objective is to achieve better economy, as well as improve cost efficiency.

F-PBPA consists of five main phases: Data Collection, Technical Optimization (TeO), Economic Optimization (EcO), Constrained Optimization (CoO), and Evaluation. In this thesis, two railway planning problems are formulated in Mixed Integer Linear Programming: Railway Preventive Condition-Based Tamping Scheduling Problem (RPCBTSP), which is presented in Papers 1-2, and Railway Track Possession Scheduling Problem (RTPSP), which is presented in Paper 3. The proposed models are tested based on the real data collected from two Danish railway corridors. A comparison of the results obtained by using the proposed PDSS with the result obtained from the literature (RPCBTSP) and the current practice (RTPSP), shows a cost reduction for both scheduling problems.

The proposed PDSS (F-PBPA) represents a step forward in solving railway scheduling problems. It can help Infrastructure Managers (IMs) gain a better understanding of the application of optimization in railway planning tasks. There are three optimization phases, TeO, EcO and CoO, that can be performed in sequence. First carries out a technical optimization (EcO), in which the minimal maintenance work can be identified by pure technical conditions. This is followed by an economic optimization (EcO), which results in an economic plan covering the same technically defined maintenance needs

while minimizing the costs. Finally, constrained optimization (CoO) includes additional constraints and it allows the railway expert to adjust input parameters, thereby to obtain alternative maintenance plans.

PO-PBPA contains another systematic phase based process. With a focus on Life Cycle Cost (LCC), PO-PBPA can guide IMs, step by step, to estimate the total project cost for railway projects and to identify the solutions that are economically advantageous. Paper 4 suggests a new LCC framework for IMs to consider costs at the strategic planning level, and Paper 5 considers costs at the project planning level. The case studies show that LCC has influence on the decisions regarding the choice of the track possessions. Similarly, it appears that decisions may change compared to today's practice if other LCC elements are included into the cost estimation, e.g., passenger loss due to delay.

A phase-based process such as the proposed PDSS, has great potential to support railway IMs to improve maintenance planning in practice, and reduce the overall costs without affecting railway infrastructure quality.

RESUMÉ (DANSK)

Vedligeholdelse af jernbanen er forbundet med store omkostninger for infrastrukturforvalteren, og udførelsen af vedligeholdelsesarbejder kan betyde sporspærringer der kan være til gene for togoperatører og passagerer. Planlægning af vedligeholdelse er således vigtig både af hensyn til økonomi og drift.

Denne afhandling præsenterer to typer fasebaserede beslutningsstøttesystemer, hhv. funktions fasebaseret planlægning (F-PBPA) og procesorienteret fasebaseret planlægning PO-PBPA. Disse anvendes til beslutningsstøtte på strategisk niveau til planlægning af projektbaserede vedligeholdelsesaktiviteter, til at opnåbedre økonomi for vedligeholdelsesprojekter samt en forbedret omkostningseffektivitet.

F-PBPA består af fem hovedfaser: Dataindsamling, teknisk optimering (TeO), økonomisk optimering (EcO), (tilføjelse af) optimeringsbetingelser (CoO) og evaluering. I denne afhandling er to planlægningsproblemer inden for jernbanen formuleret og modelleret i lineære blandede heltalsprogrammer: Planlægning af forebyggende ballaststopning som er præsenteret i artiklerne 1-2, og planlægning af sporspærringer som er præsenteret i artikel 3. Data er indsamlet fra to jernbanekorridorer i Danmark. Modellerne er testet i to casestudier, der er baseret på de indsamlede data. En sammenligning af resultaterne som opnås ved anvendelse af de foreslåede PDSS for RPCBTSP, med resultater fra metoder i litteraturen, viser en omkostningsreduktion på op til 40%. Ved justering af nogle nuværende sporspærringsplaner for RTPSP opnås en omkostningsreduktion.

Den foreslåede PDSS (F-PBPA) udgør et fremskridt i at løse planlægningsproblemer inden for jernbanen, og kan hjælpe infrastrukturforvalteren til at opnåen bedre forståelse af anvendelsen af optimering i planlægningen. Der indgår tre optimeringsfaser TeO, EcO og CoO, som kan udføres i rækkefølge. Først foretages en teknisk optimering (TeO), hvor det minimale antal vedligeholdelsesarbejder identificeres når der alene vurderes ud fra tekniske forhold. Derefter foretages en økonomisk optimering (EcO), som resulterer

i en økonomisk optimal vedligeholdelses plan, som både dækker de teknisk definerede vedligeholdelsesbehov, samtidig med at de relaterede omkostninger minimeres. Til sidst en betinget optimering (CoO) hvor der medtages yderligere betingelser. Her har en jernbaneekspert mulighed for at foretage justeringer af inputparametre og tilføje nye betingelser, hvorved der kan laves alternative vedligeholdelsesplaner.

PO-PBPA er en anden systematisk fasebaseret proces. Med fokus på levetidsomkostninger (LCC) kan PO-PBPA vejlede infrastrukturforvalteren, trin for trin, i at estimere de samlede projektomkostninger for vedligeholdelsesprojekter, og til at finde de løsninger som er økonomisk fordelagtige. I artikel 4 præsenteres en ny ramme for håndtering af levetidsomkostninger på det strategiske planlægningsniveau, og i artikel 5 for levetidsomkostninger på projektplanlægningsniveau. Casestudierne viser, at LCC har betydning for de beslutninger der tages ved udfærdigelsen af planerne for anvendelse af sporspærringer. Ligeledes vises det, at beslutningerne kan ændre sig i forhold til i dag hvis andre LCC elementer medtages i omkostningsestimeringen, f.eks. fald i passagertal.

En fasebaseret proces, som de foreslåede PDSS, har et stort potentiale til at støtte infrastrukturforvalteren til at forbedre vedligeholdelsesplanlægningen i praksis, og reducere de samlede projektomkostninger uden at det vil påvirke jernbaneinfrastrukturens kvalitet.

OVERVIEW OF PAPERS

Papers	Status
Paper 1: *Optimization of Preventive Condition-Based Tamping For Railway Tracks* *Min Wen, Rui Li, Kim Bang Salling* **European Journal of Operational Research** *(ISI, impact factor of 2015: 2.679)* *Volume 252, Issue 2, pp. 455-465*, 2016 Conference • **IC-ARE 2015**: International Congress on Advanced Railway Engineering 2015, Turkey, *presented and published* • **ICREM 2015**: International Conference on Railway Engineering and Management 2015, Copenhagen, Denmark, *presented* • **IALCCE 2016**: International Symposium on Life-Cycle Civil Engineering 2016, Delft, The Netherlands, invited, *presented and published*	Published
Paper 2: *A Phase-Based Decision Support System For Railway Preventive Condition-Based Tamping* *Rui Li, Min Wen, Kim Bang Salling* **European Journal of Transport and Infrastructure Research**	Submitted

Papers	Status
Paper 3: *Optimal Scheduling Of Railway Track Possessions In Large-Scale Projects With Multiple Construction-Works* *Rui Li, Roberto Roberti* **Journal of Construction Engineering and Management** *(ISI, impact factor of 2015: 1.152)* *Volume 143, Issue 2, 2017* Conference • **COMPRAIL 2014**: Computers in Railways 2014, June 24-26 Rome, *presented and published* • **Den Danske Bane Konference 2015**: The Danish railway conference 2015, Copenhagen, Denmark, *presented*	Published
Paper 4: *Framework For Railway Phase-based Planning* *Rui Li, Alex Landex, Otto Anker Nielsen, Steen Nørbæk Madsen* Conference • **Trafikdage 2013**: Annual Transport Conference at Aalborg University 2013, Aalborg, Denmark *presented and published*	Published
Paper 5: *The Potential Cost From Passengers and How It Impacts Railway Maintenance and Renewal Decisions* *Rui Li, Alex Landex, Otto Anker Nielsen, Steen Nørbæk Madsen* Conference • **Trafikdage 2013**: Annual Transport Conference at Aalborg University 2013, Aalborg, Denmark *presented*	Presented

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Chapter 1

INTRODUCTION

This chapter gives an introduction to the thesis. It firstly describes the motivation of the research. Thereafter, the research questions and the collected data are introduced. At last, the structure of the thesis is presented.

1.1 Motivation

Through the last decade, maintenance of railway infrastructure has become an increasingly important topic in Denmark as well as throughout the entire Europe (Jovanovic (2004), Zoeteman (2001), Zoeteman (2006), Nielsen (2013), Li et al. (2013a)). Evidently, massive investments are needed to govern, implement, plan and execute the latter. This thesis investigates and hence exploits a new planning approach in terms of reducing (scheduling) one aspect herein, namely the track possessions during maintenance. Obviously, as the railway gets more and more degraded; tracks, signals, etc., must be either replaced or maintained. Therefore, in many cases, it is necessary to close down entire sections of the railway – corresponding to delays in train operation and nuisance for passengers and freight operators. Thus, it becomes even more important to secure a new planning approach to railway maintenance in terms on how to possess the tracks and scheduling whilst at the same time operate under an extremely tight budget restriction.

Importantly, as part of the track possession planning one key aspect within railway maintenance tasks are investigated, condition-based tamping. Today, tamping are only condition-based i.e. scheduled according to short term (quarterly) requirements in literature referred to as preventive condition based tamping. Scheduling Preventive condition-based tamping maintenance for a given railway track over a planning horizon can be further explored in e.g. (Vale et al. (2012),Vale and Lurdes (2013), Veit (2006),Budai and Dekker (2004), Budai et al. (2006), Jimenez-Redondo et al. (2012), Uzarski and Mcneil (1994), Kong and Frangopol (2003), Macke and Higuchi (2007), Jensen (2013)). In essence the railway tracks are divided into a number of consecutive sections of typically

200 meter each. The tamping machine travels on top of the railway track and applies preventive tamping if necessary. The track quality is measured by the standard deviation of survey spots for each section. Tamping decisions (tamping time and tamping sections) are based on the condition-based principal, where track quality degrades continuously, and maintained by tamping (it is not allowed to exceed the threshold limits).

This thesis proposes to implement a new planning Decision Support System (DSS), as illustrated in Figure 1.1, for railway maintenance scheduling at a strategic level. From Figure 1.1 a set of input parameters such as demand, cost and maintenance rules (i.e. Possession time, etc.) are fed into the DSS, where the output (solutions) are expected to be generated in a systematic approach which is easy to understand in real-life cases. In other words, the relevant costs, railway infrastructure, traffic, maintenance rules, and expert adjustments can be included in the planning processes if needed. The goal is to reduce the overall costs without affecting railway infrastructure quality and operation.

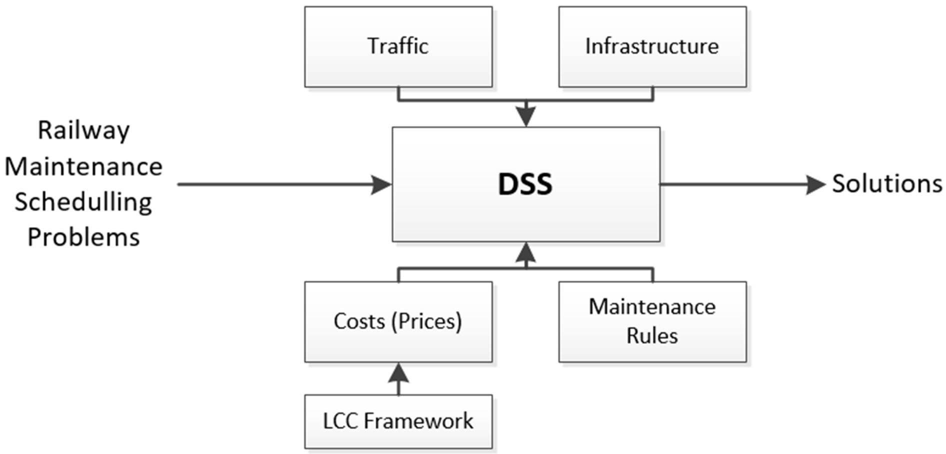

Figure 1.1. Functionality of the proposed Decision Support System, LCC-DSS model

1.2 Research Question

This study is carried out to address scheduling problems for railway infrastructure project from the strategic level. Furthermore, it seeks to provide a systematic decision support system for railway Infrastructure Managers, government officials, etc., to decide when and where to perform which maintenance or construction operations over a given planning horizon. Thus, the overarching purpose is to construct a practical planning decision support system with the main objective to reduce the overall cost in railway infrastructure maintenance.

Concurrently, through this thesis a valid, flexible and functional "Phase-based Decision Support System" (Papers 1-3), from a Life Cycle Cost (LCC) perspective (Papers 4-5), to plan railway infrastructure maintenance (and projects) more economically, i.e. cost-effective has been developed. The proposed DSS provides decision support in terms of the ability to introduce and thus optimize life cycle costs through a systematic phase based process. Therein, the railway Infrastructure Managers can be assisted in estimating costs both at the strategic level (Papers 3-5) and at the project level (Paper 1-2). Cost-oriented aspects of the plan-evaluation is implemented in the DSS with which an optimal solution via the optimization phases can be achieved.

Figure 1.2 illustrate additionally the particular research area for the five papers.

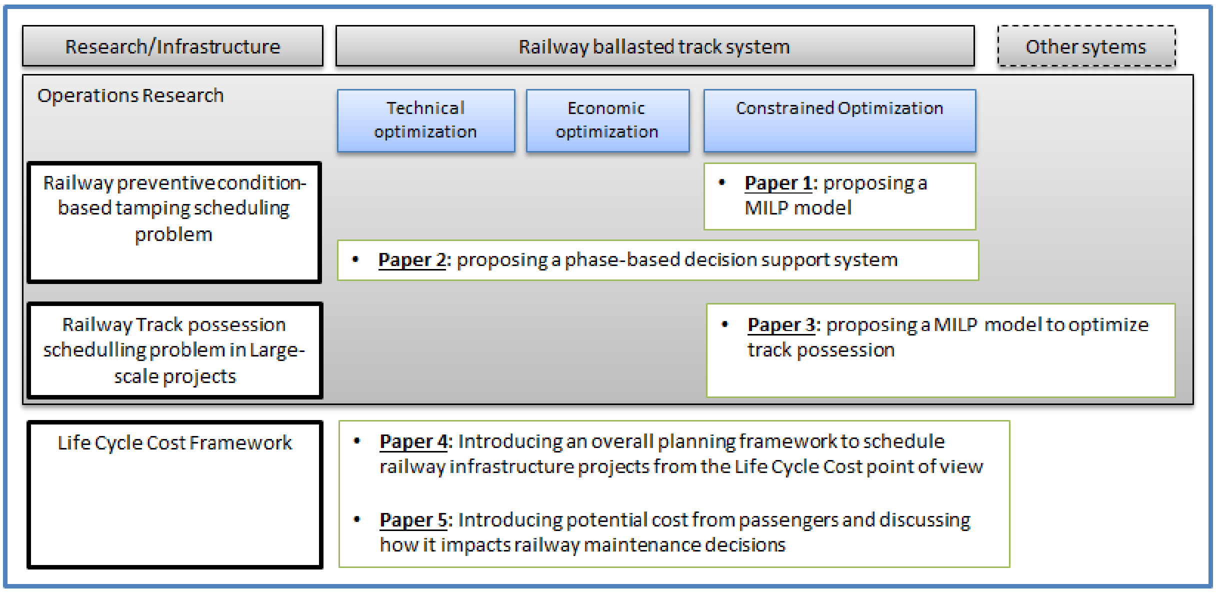

Figure 1.2. The Scope of this PhD research

Railway infrastructure in this thesis refers to the traditional ballast track system. The other railway infrastructures such as signalling system, power supply, and overhead catenary system, are only relevant to railway track possession scheduling problem covered by Paper 3.

The application of Operations Research (OR) is carried out by the journal papers (Papers 1-3) and the Life Cycle Cost (non-OR approach) framework is applied by the conference papers (Papers 4-5), as illustrated in Figure 1.2. Papers 1-3 bring the main contributions to this research. The DSS is based on two well-established OR approaches to support railway scheduling i.e. 1) the Railway Preventive Condition-Based Tamping Scheduling Problem and 2) the Railway Track Possession Scheduling Problem for large-scale projects. Finally, included data from real-life cases have been collected for each of the two scheduling problems.

1.2.1 Railway preventive condition-based tamping scheduling problem

Railway Preventive Condition-Based Tamping Scheduling Problem (RPCBTSP) is to schedule condition-based tamping maintenance for a given railway track over a planning horizon (Vale et al. (2012), Vale and Lurdes (2013), Veit (2006), Budai and Dekker (2004), Budai et al. (2009), Budai et al. (2006), Jimenez-Redondo et al. (2012)). The problem is to determine when to perform the tamping on which section. The objective is to minimize the Net Present Costs (NPC) considering the technical and economic factors: i.e., 1) track quality (the standard deviation of the longitudinal level) degradation over time; 2) track quality thresholds based on train speed limits; 3) the impact of previous tamping operations on the track quality recovery; 4) track geometrical alignment; 5) tamping machine operation factors; and finally 6) the discount rate.

The research on RPCBTSP are presented in two papers, Paper 1 and Paper 2. Paper 1 (Wen et al. (2016)) proposes a Mixed Integer Linear Programming (MILP) model to improve the existing models in the literature. Paper 2 (Li et al. (2017)) proposes a new phase-based framework to overcome the existing practical planning challenges and reduce the actual preventive tamping cost. The details of phased-based decision support system are introduced in Chapter 3.

1.2.2 Railway track possession scheduling problem

Railway Track Possession Scheduling Problem (RTPSP) is to schedule the track possessions for a large-scale railway project with multiple construction tasks (Yang and Chen (2000), Vanhoucke (2005), Rambøll (2011)). Each task has to be implemented within the given planning horizon under one or multi track possessions, e.g., night time, full-day closures, weekends etc. (Budai et al. (2009), Madsen et al. (2014)). The time and cost to complete each task depend on the selected track possessions. The RTPSP is to find an optimal economic plan (when to implement which task under which track possession) to carry out given construction tasks while satisfying the operational constraints, such as precedence relationships between tasks, and the limits on simultaneous tasks etc.

Distinguishing from the current literature (Johnston (1981), Tang et al. (2014), Reda (1990), Harmelink (2001)) on linear scheduling method (LSM) or (Richter and Weber (2013), Kim and Kim (2010), Kim (2011), Wilmot and Mei (2005)) on Case-based reasoning (CBR) methods or (Nemhauser and Wolsey (1988), Taha (2006), Chen et al. (2010), Demeulemeester and Herroelen (2002)) on mathematical modelling, Paper 3 defines the research problem, RTPSP, from a totally new perspective. It proposes a MILP model to support decision maker to filter out the best possible track possession patterns from thousands of possible combinations in a reasonable running time.

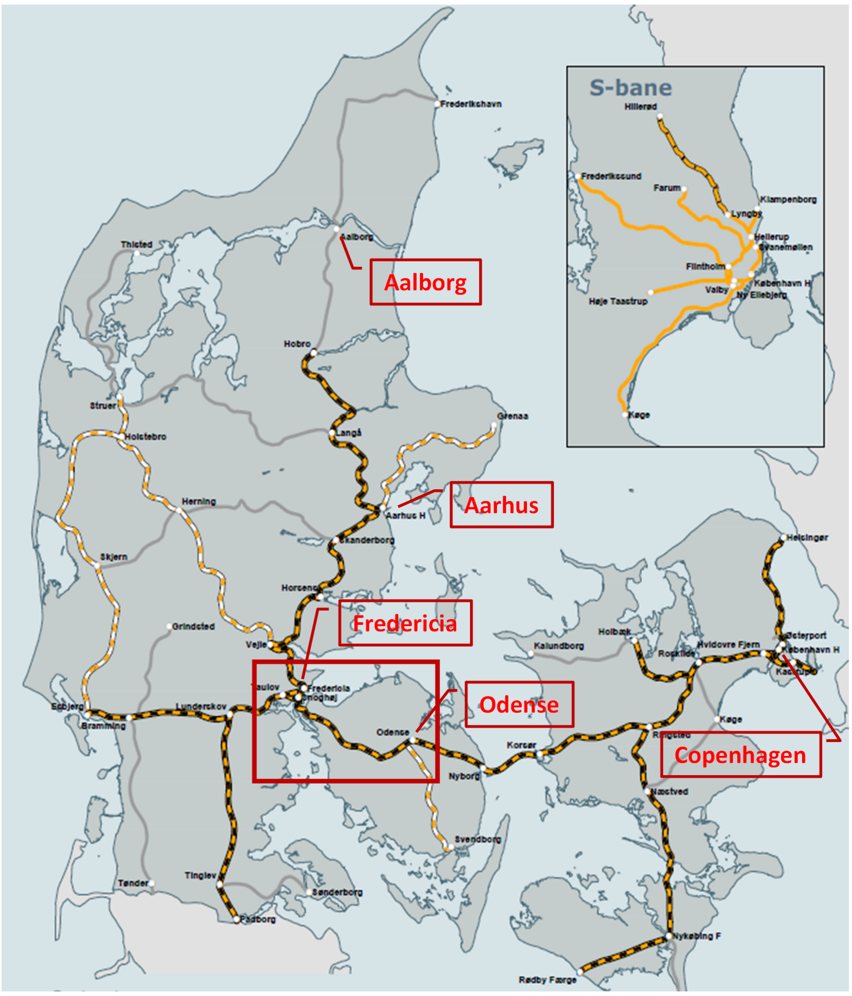

Figure 1.3. Railway corridor Od-Fa

1.3 Research Data

The thesis works on real case examples. The real data are collected from Banedanmark on two railway corridors i.e. Odense to Fredericia (Od-Fa) and Ringsted to Rødby (Rg -Rb).

1.3.1 Odense - Fredericia corridor

The Odense - Fredericia railway corridor (Od-Fa), with a length of 57.2 km, is a part of the busiest interregional main line connecting the top four biggest cities in Denmark i.e. Copenhagen, Odense, Aarhus and Aalborg, as depicted in Figure 1.3.

The Od-Fa corridor comprised of a double-track structure is heavily used by both national and international (Sweden - Germany) passenger and freight trains. In the experiment, railway preventive condition-based tamping scheduling problem (RPCBTSP) is tested on the open track between stations and moreover only on the right track.

The infrastructure data applied to the case studies in Paper 1 and Paper 2 includes,

- Asset information
  - Asset type for rail, sleeper and ballast
  - Installation years for rail, sleeper and ballast
- Track geometry information
  - Longitudinal and horizontal designed track geometries
  - Track geometries conditions (2007 to 2012)
  - Track sections
  - Track irregularities thresholds
- Traffic information
  - Traffic density and axle load
  - Yearly tonnage
  - Operating Speed
- Historical maintenance information
  - Preventive tamping records
  - Tamping recovery
- Tamping information
  - Tamping machine type
  - Tamping and driving speed
  - Tamping machine limits etc.
- Economic information and others
  - Tamping budgets
  - Discount rate

1.3.2 Ringsted - Rødby corridor

The Fehmarn Belt project at the Danish side, illustrated in Figure 1.4, includes both a new tunnel between Rødby and Puttgarden, and the corresponding onshore facilities upgrading both roads and railways. The railway construction work between Ringsted and Rødby (Rg-Rb) includes four main activities, namely, electrifying the Rg-Rb line, constructing 55 km of new track to upgrade the entire Rg-Rb corridor to double track layout, upgrading the existing tracks for the speed of 200 km/h, building and rebuilding the bridges along the railways (Banedanmark (2012a)).

Because the South section of the Fehmarn Belt project connects Vordingborg and Rødby (Vb-Rb) with an existing single track; part of the rail traffic has to be stopped for certain construction tasks. Four types of track possession i.e. night possession, interval possession, weekend possession and full-closure in summer, are to be scheduled for the planning horizon up to five years.

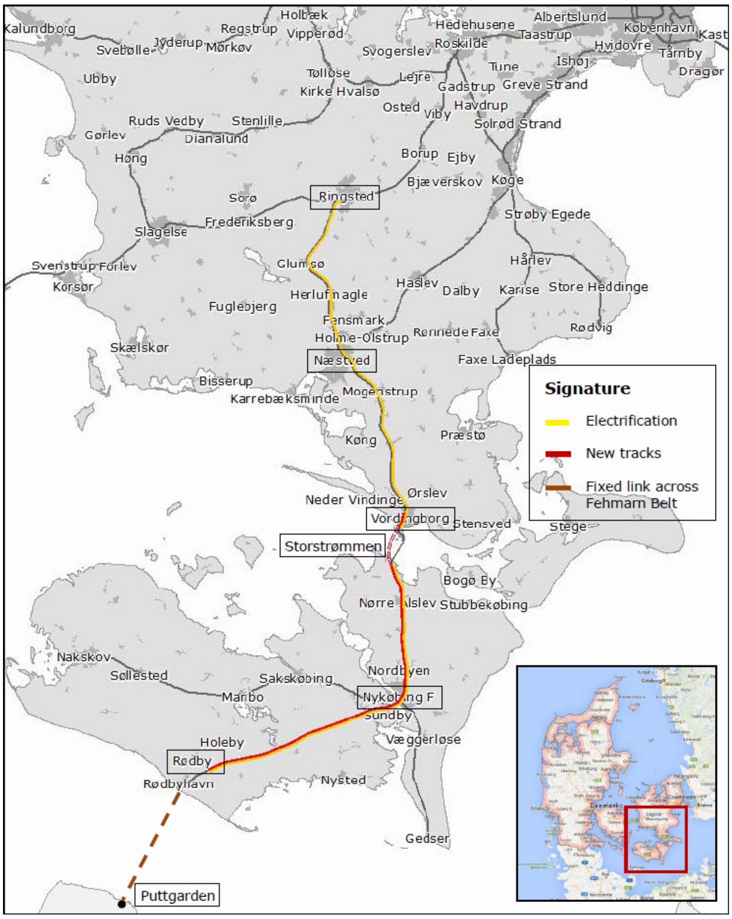

Figure 1.4. Rd-Rb railway corridor and construction tasks

The real data presented in the case study of Paper 3 includes,

- Railway tasks and possible possessions
  - Construction tasks
  - the possible possession for each task
- Operational constraints
  - Limit of simultaneous working tasks
  - Continuity of the operation of each tasks
  - Incompatibility between tasks
  - the track possession pattern for the whole project
- Economic and other factors
  - Different costs
  - Working efficiency in different track possessions
  - Labor, materials and machinery percentage for each task

1.4 The Structure Of The Thesis

The remainder of the thesis is organized as follows. Chapter 2 introduces railway infrastructure, the maintenance tasks and the current scheduling challenges in practice. Chapter 3 presents the proposed Phase-Based Decision Support System and a Life Cycle Cost framework. Chapter 4 discusses the pros and cons applying the proposed methods in the Danish case studies. Chapter 5 highlights the main contributions of this thesis, and Chapter 6 presents the conclusions and the suggestions for future research. Finally, five papers are attached to illustrate the detailed mathematical models and phase-based decision support systems. Figure 1.5 illustrates the contents for Chapters 1-6.

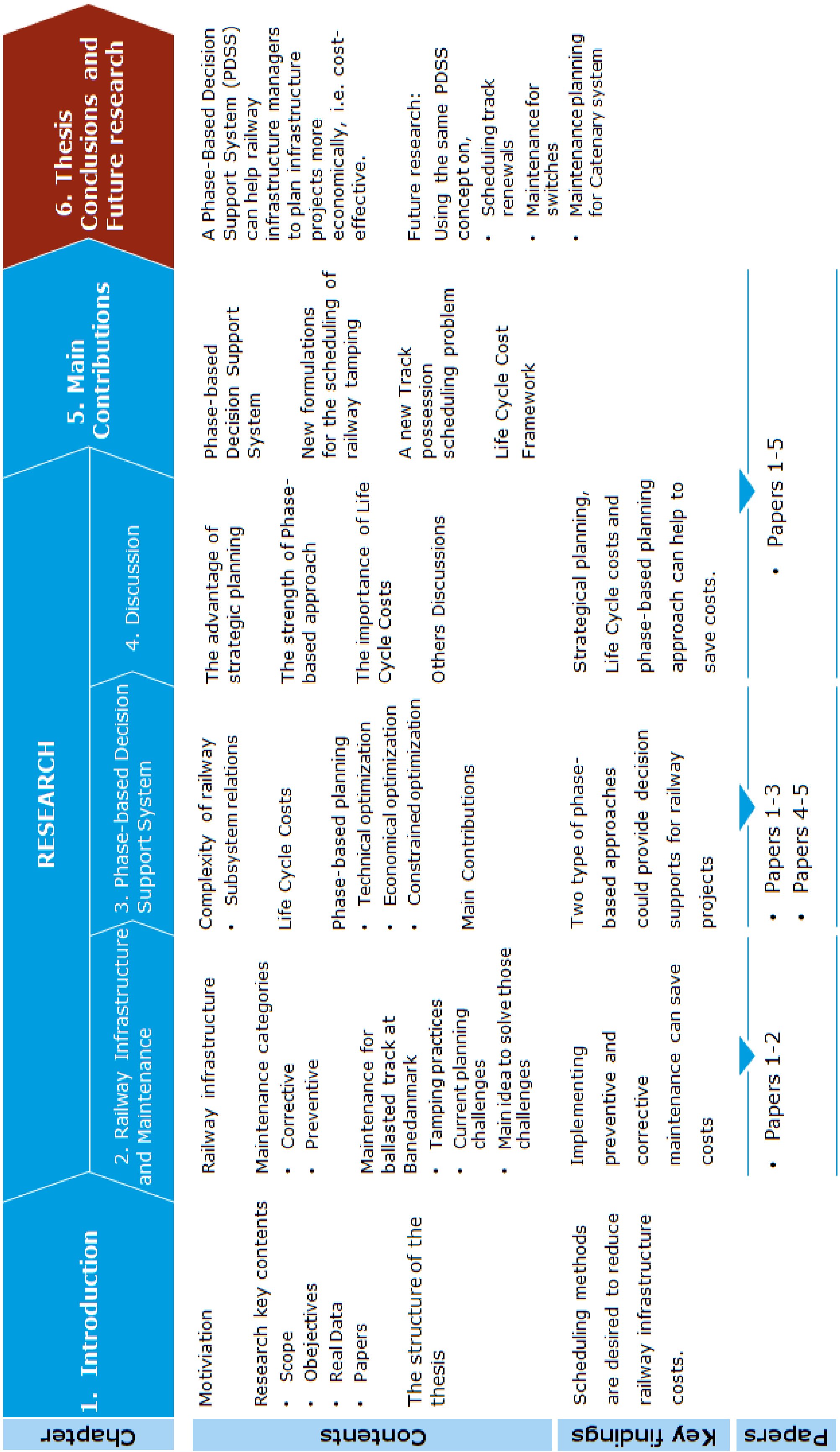

Figure 1.5. The structure of the PhD Thesis (Chapters 1-6)

Chapter 2

RAILWAY INFRASTRUCTURE AND MAINTENANCE

This chapter introduces railway infrastructure and today's maintenance. Firstly, Section 2.1 introduces railway infrastructure in general and explains why the railway ballasted track system is chosen for this research. Section 2.2 defines railway maintenance and describes different maintenance categories. Section 2.3 presents the particular maintenance activities for railway tracks. At last, Section 2.4 presents the current practices of preventive condition-based tamping at Banedanmark and briefs the challenges.

2.1 Railway Infrastructure

It is essential to understand how the railway is designed and constructed in order to understand the maintenance works and how they are carried out to keep railways in good conditions. This section will firstly introduce the common railway infrastructure, and then the track system in particular.

Modern railway infrastructure is a complex system containing four main sub-systems, i.e. track system, signalling system, overhead catenary system and power supply system, while the traditional railway infrastructure (non-electrified) contains only track system and signalling system. The layout of modern railway infrastructure is illustrated in Figure 2.1, where the track system is composited by rail, sleeper, ballast and substructure; the signalling system includes physical signalling and cables; the overhead catenary system contains support mast frame and overhead contact wires; and the power supply system (not showing in Figure 2.1) provides the electronic current into the overhead catenary system.

Besides these systems, there exist also other railway related infrastructures, see Figure 2.2. Everything are linked. This builds up the current railway infrastructure.

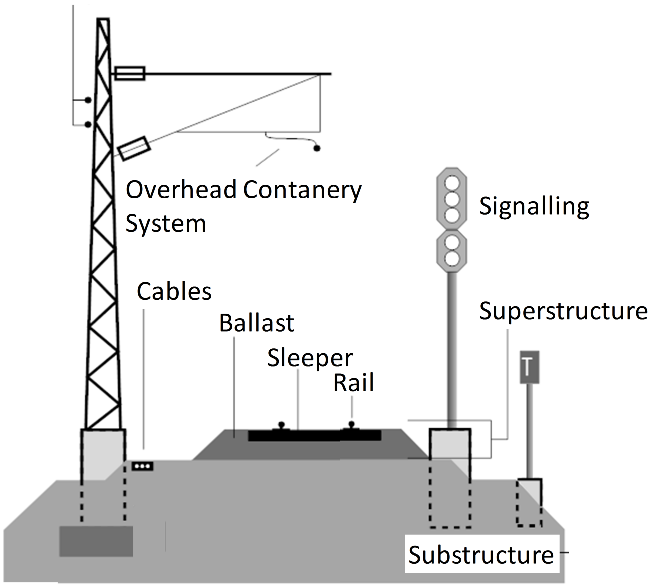

Figure 2.1. Cross section layout of railway infrastructure (Single track)

Railway track system have been chosen for this study because of the great requirements for ongoing railway track maintenance in Denmark. Right now, it is under great interests of railway infrastructure mangers, Banedanmark, to find out the best time to implement track maintenance (Jensen (2013), Nielsen (2013)).

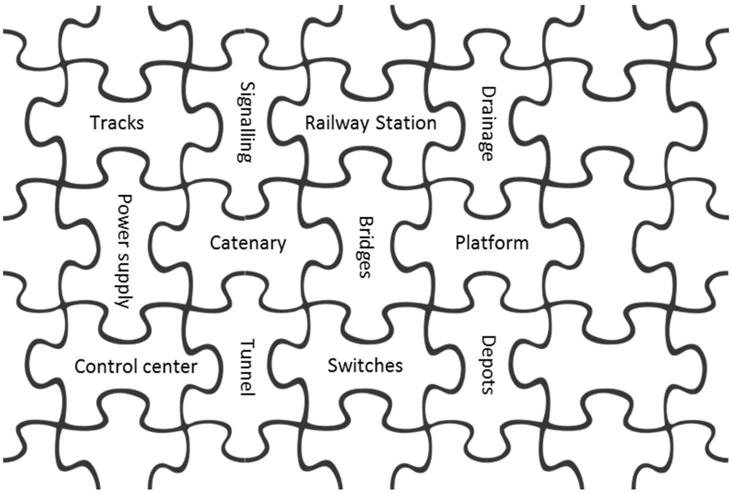

Figure 2.2. Railway related infrastructures

2.1.1 Railway tracks

The traditional railway track called ballasted track, is composited by rail, sleeper, fastening, ballast and subgrade. The functions of track system are (Lichtberger (2007)),

- Carry vehicles without risk of derailment
- Accept vertical and horizontal forces from vehicles
- Conduct these forces through the track structure and the ballast bed into the subgrade
- Ensure good travelling comfort
- Deliver a high level of operational availability.

The high contact forces and vehicle guidance forces impose heavy demands on the rails. Railway track system is therefore developed in the way to transfer the forces in the restriction of vibration and noise level (Veit (2012)). The rails are made of I-shaped steel bars on which the rail vehicle wheels are running. Sleepers form the support for the rails, transferring the load from the vehicles into the ballast. (Andersson (2001)). Figure 2.3 demonstrates the main components of common ballasted track structure.

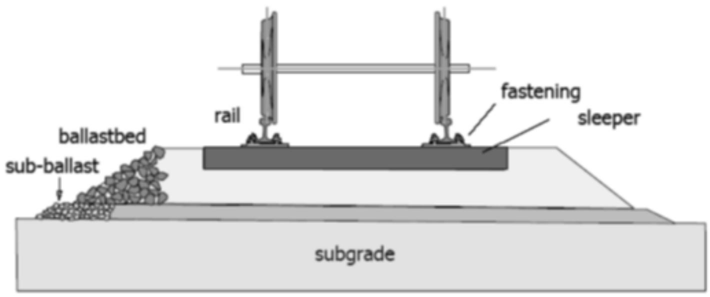

Figure 2.3. Railway structure - Ballasted track

Ballasted track has a quite long history in operations. In Denmark, most of the railway lines are ballasted track except several particular tunnels and bridges, where slab tracks are installed. The standards regarding ballast track installation/maintenance/renewals etc., are well established (Nielsen (2013)). Most technical difficulties, for example installing railway track on soft subsoil, have been well solved. Because ballasted track has been widely installed, the prices for ballasted track are relative low compared to the new slab track. The historical data are well documented on the main lines in Denmark, (Jensen (2013)).

Track geometry

To schedule railway track maintenance, it is important to understand track geometry and track irregularities. Track geometry is a three-dimensional (3D) geometry of track layouts and associated measurements used in design, construction and maintenance of railway tracks. In practices, track geometry is normally be illustrated by using horizontal alignment and longitudinal alignment, illustrated in Figure 2.4.

A 2D track geometry is composed by straight lines, curves (with fixed radius), and transition curves. A transition curve containing various radius is normally used to link straight line to curve, or link two curves with different directions.

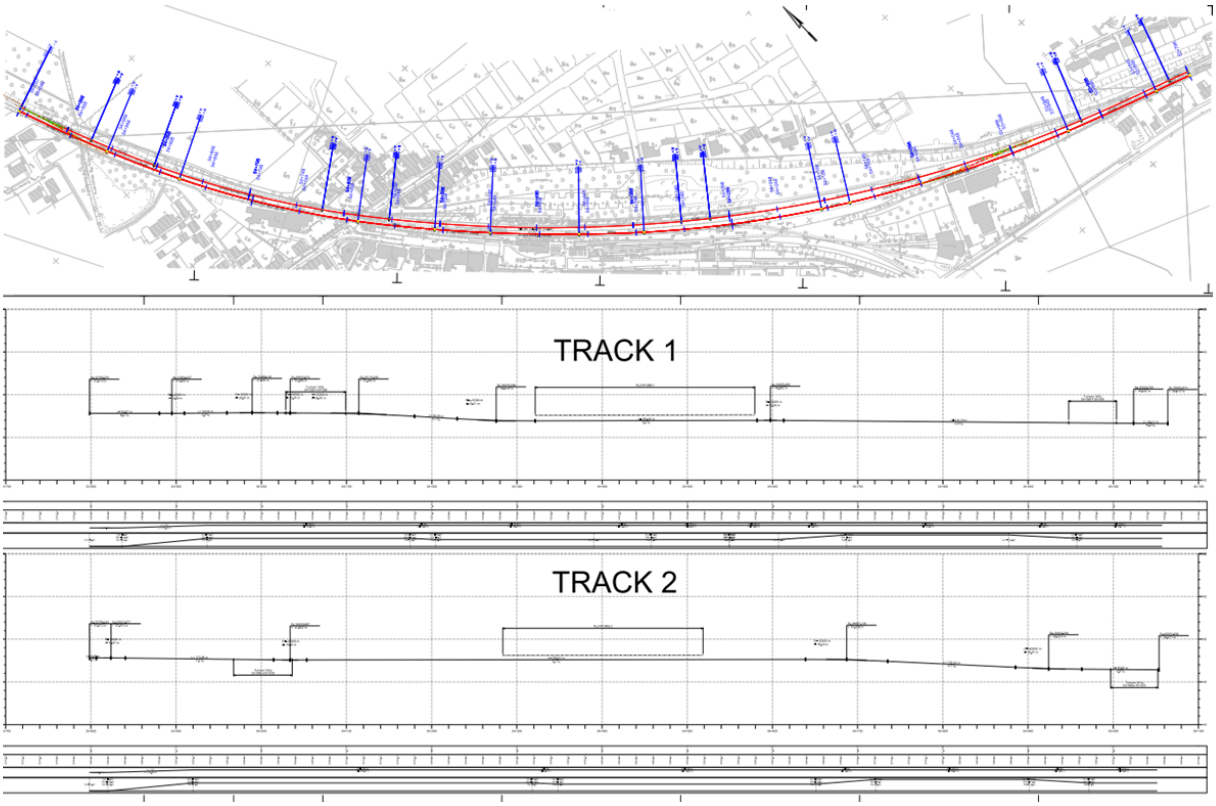

Figure 2.4. Track geometries (From top to botttom: Horizontal alignments for Tracks 1-2, Longitudinal alignment for Track 1, and Longitudinal alignment for Track 2)

Track irregularities

When the ballasted track system reacts to the forces imposed by passing traffic, it can generate deviations from the original installation position. If the deviation exceeds tolerated levels, it is defined as track irregularities (Corshammar (2006)), see Figure 2.5. The nominal track geometry is the designed geometry of the railway track, referring both to horizontal alignment and longitudinal alignment.

Ballasted track is not a "firmed" structure, like road pavement, to absorb traffic forces and reduce vibration. Irregularities can thus develop much faster. Therefore, track geometry survey and track maintenance, for example tamping, need to implement regularly for railways. More details about track irregularities regulation in Denmark will be introduced in Section 2.3.

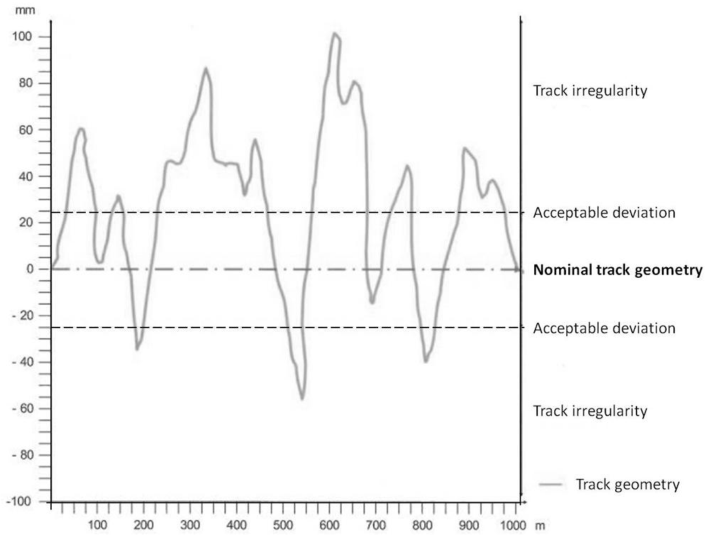

Figure 2.5. Illustration of track irregularities. (Corshammar, Perfect Track, 2006)

2.1.2 Overhead catenary system and power supply system

In Denmark, only some parts of the main railway lines are electrified. The others only operate diesel trains today. The rail transport system in Denmark consists of 2,633 km of railway lines, where Banedanmark is in charge of 2,132 km including 2,342 bridges (Jensen (2013)). In Figures 2.6, the left map shows the railway network, while the right shows the electrified railway lines.

For railway power supply system, the main lines in Denmark are using 25kV 50 Hz AC-system, which is directly powered from national High Voltage (HV) grid. In Great Copenhagen area in Denmark, S-trains operated in urban area are using DC-system which has a separated infrastructure set-up.

2.1.3 Signalling system

The existing Danish signalling is based on traditional relay-technology, color light signals, track circuits for train detection and a ATC system on major lines. Today the main and regional lines are operated from 3 large control centers and 11 small ones. A separate large and relatively modern control center manages the urban S-trains in the Great Copenhagen Area (Banedanmark (2010)).

All signalling to the train drivers is regulated by the Danish rule book SR75 (Banedanmark (2010)), which contains a specific set of Danish rules developed over a period of 100 years. The equipment has now aged to a point where the majority of the present systems are past their technical service lives. Figure 2.7 shows the existing signal service life as per 2020 (Banedanmark (2010)). In January 2009, the Danish parliament decided to fund a 3.2

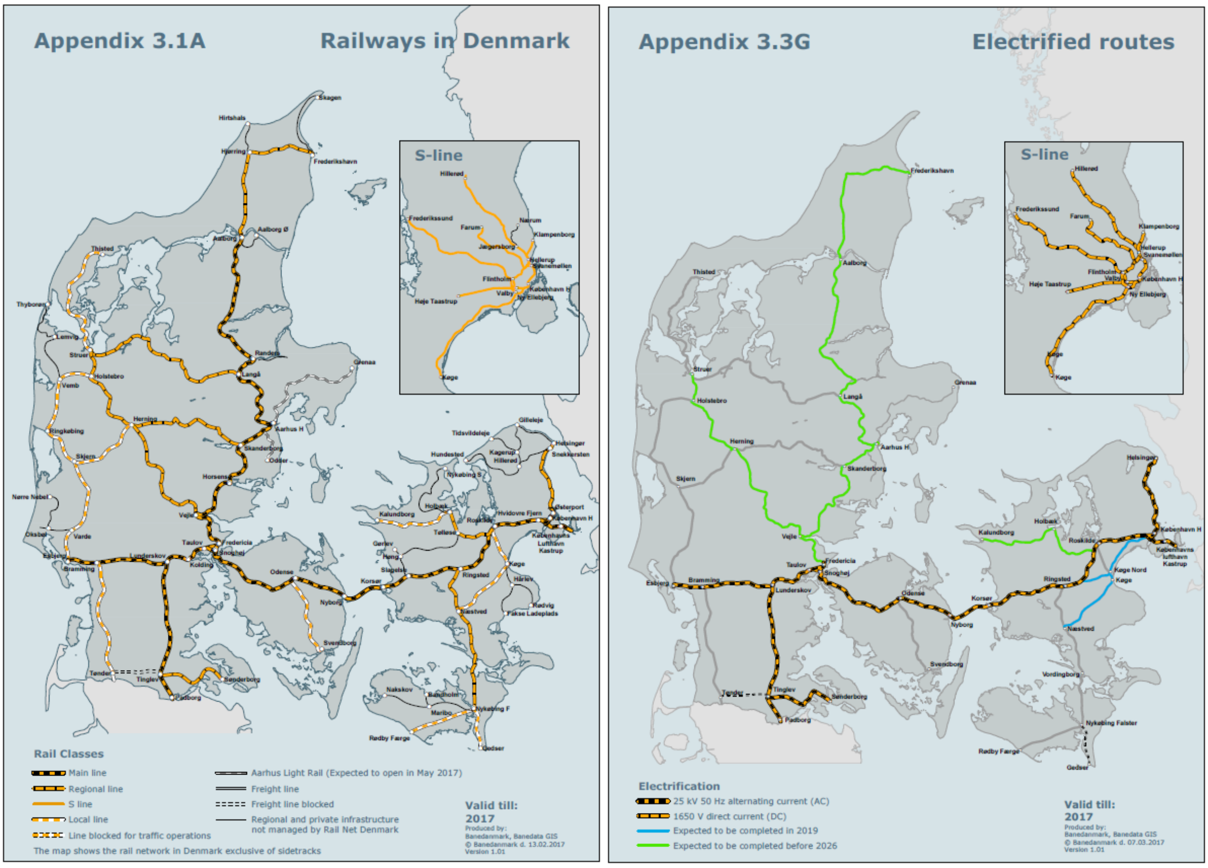

Figure 2.6. Left: Danish railway network, owned by Banedanmark (Banedanmark (2017b)). Right: Electrified railway lines, owned by Banedanmark (Banedanmark (2017a))

billion Euro replacement programme of renewing all Danish railway signalling before 2021 to obtain the Economy of Scale. The future signalling will be replaced by ERTMS Level 2 for long distance railway lines and CBTC technology for the urban S-trains network (Banedanmark (2010)).

Because the previous maintenance strategy for signalling will not be valid after the switching to the new one, the signalling system is not the focus railway infrastructure for this study.

2.2 Railway Maintenance

Maintenance is defined as "The process of keeping something in good condition", *Oxford dictionary*. For railway maintenance, it means the work to be carried out to keep or improve the states of railway infrastructure (Esveld (2001)). Without appropriate supply of maintenance, railway infrastructure assets deteriorate and the defects can cause accidents.

Figure 2.7. Service life on signalling assets as per 2020 (Banedanmark (2010))

Infrastructure managers may have to interrupt the use of the railway assets, which leads to the problems of train punctuality, transport transition and railway capacity. Therefore, it is necessary to plan and execute maintenance appropriately.

Railway maintenance can be grouped into two main categories, i.e. corrective maintenance and preventive maintenance. Preventive maintenance can be divided into two sub-categories, (preventive) Norm-based maintenance and (preventive) Condition-based maintenance, demonstrated in Figure 2.8.

Corrective maintenance is the operation to fix a railway asset failure every time when it is encountered during the asset lifetime (Fumeo et al. (2015)). Corrective maintenance is carried out usually by restoring the asset status to normal conditions, or by replacing a broken part with a new one. This repair usually is very expensive. The combination of direct costs (materials, labor and machinery) and indirect costs (service disruptions) often results in an unaffordable situation. Comparing to corrective maintenance, the time

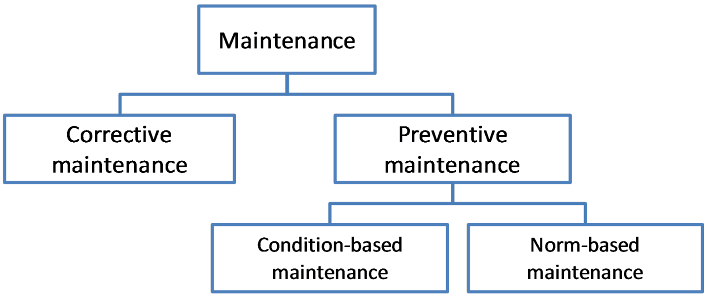

Figure 2.8. Railway maintenance categories

to carry out preventive maintenance is before the occurrence of assets failure and the purpose is to reduce the probability of failure and the corrective maintenance. In general, preventive maintenance is to keep railway assets in satisfactory operating condition. The tasks normally include the activities of systematic inspection, detection, and correction of incipient failures before they develop into major defects (Esveld (2001), Jensen (2013)).

For example, corrective maintenance in Denmark is to fix the serious track defects, e.g. broken rail/sleeper/fastening and track geometry defect Class 4, which could cause safety related risks such as derailment (See Section 2.3 for the details about track defect Class 4 definition at Banedanmark). Corrective maintenance operations are very important and they require immediate actions which are not allowed to be postponed nor cancelled. If only implementing corrective maintenance, the cost for corrective maintenance is expensive and not controllable due to its "random" feature of the failure occurrences in terms of precise time and locations. Instead, preventive maintenance can be performed regularly to prevent the development of minor track irregularities and therefore reduce the overall maintenance costs. For instance, rail grinding is often executed to restore the rail profile and remove irregularities from worn rail track to extend its life and reduce the possibility of broken rails.

Preventive maintenance can be further divided into Norm-based maintenance and Condition-based maintenance. Norm-based maintenance is namely the maintenance tasks which are carried out according to norms and standards. The norm-based maintenance is often time dependent intervals determined according to reliability measures, such as Mean Time Before Failure (MTBF). For example, when a new track is installed, it is regulated that a tamping should be carried out right after the installation, and also after one year (Rail Standard BN1-38-4 (2011)). The drawback of Norm-based maintenance is obvious that the maintenance operations are executed not according to the asset health status but timing, as they get statistically close to a probable failure. In practice, this part of maintenance cost is often integrated into fixed cost category; Instead, condition-based maintenance suggests a prognostic attitude towards maintenance, that can be realized by constantly monitoring the conditions of an asset, and consequently allowing triggering maintenance activities only if any potential asset degradation is detected (Fumeo et al. (2015)).

This study takes a step forward, integrating an asset degradation model to predict the asset condition and optimize the schedule of condition-based maintenance. Instead of triggering maintenance activities only when the asset reaching the threshold of asset condition, the maintenance tasks can be (re-)scheduled in advance to group the maintenance and minimize cost.

2.3 Maintenance For Ballasted Tracks at Banedanmark

The ballast track has been chosen for this study to optimize the preventive condition-based maintenance. It is because the historic data for condition-based maintenance are well documented. By using those data, a new proposed method could be evaluated. Instead, the technology for the other systems, catenary, signalling, power supply systems, develop much faster. Customized solutions are implemented widely in Denmark. Data are not as well as ballasted tracks. In the rest of the thesis, railway infrastructure without particular statement will refer to the ballasted track in Denmark.

Ballasted track needs regular maintenance to remain in good order. Table 2.1 shows the factors may give impacts to track condition. Typical track maintenance tasks at BDK contain totally 40+ maintenance items. They are grouped into switches maintenance, corrective maintenance and preventive maintenance (see Figure 2.9).

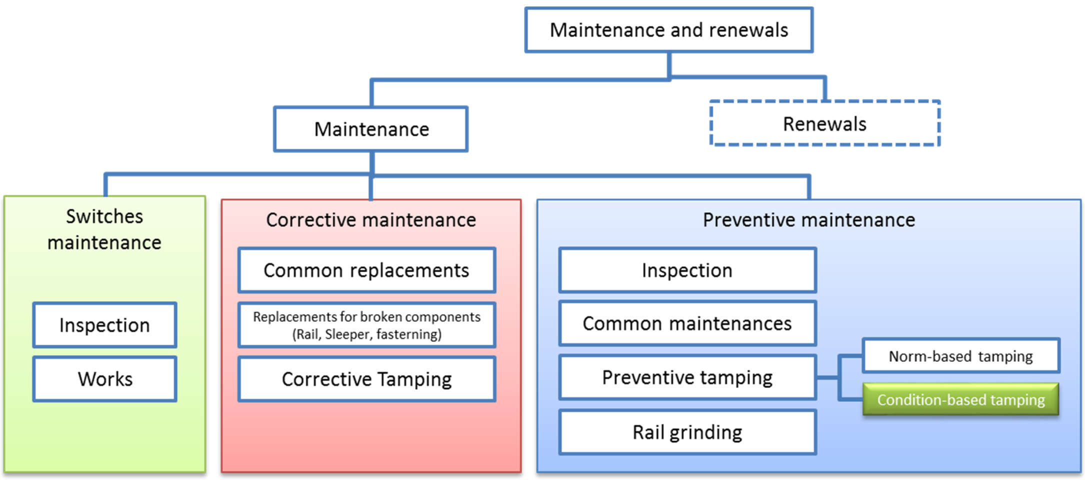

Figure 2.9. Maintenance and renewals for ballasted track

Switches maintenance is treated as a separated category for maintenance. Railway switches have a complex structure which have caused the most of the track problems

Table 2.1. Main facors that give impacts to track condition (Wen et al. (2016), Li and Roberti (2017))

Category	Factors
Density of traffic	• Main line, regional line or local line • Train density and Operation hours • Freight train • Yearly Tonnage • Running speed
S&C density	• Number of S&C • S&C complexity • Stations layout and complexity
Weather	• Snow, Rain and sunshine • Salt condition in the air (close to sea)
Rolling Stock Conditions	• Weight, Speed, Axel load, Break type • Wheels, maintenance etc.
Geometry Alignment	• Horizontal curves • Longitudinal layout
Subsoil condition	• Subsoil condition • Drainage system

from the historic records. They require a special type of maintenance machine and more maintenance operations.

Corrective maintenance for ballasted track includes three types of tasks.

- Common replacements
- Replacements for broken components (Rail, Sleeper, Fastening),
- Corrective tamping for track spot (around 15m)

Comparing to the preventive maintenance, tamping is carried out for the particular track spots around 15 meter. The small size tamping machine can some time be used. Switches maintenance and corrective maintenance are not the focus in this thesis.

Preventive maintenance for ballasted track at Banedanmark includes,

- Inspection
- Common maintenances
- Rail grinding
- Preventive tamping for track section (200 m)

Among others, preventive condition-based tamping is one of the focuses for this study.

2.3.1 Tamping for railway tracks

Railway tamping maintenance is conducted to restore track irregularities (Esveld (2001)). Tamping can be explained as compaction of the ballast in the railway track to increase the supportive effect from the ballast on the sides of and under the sleepers. The tamping vehicle has a tamping tool that consists of claws of picks that are inserted in the ballast on each side of the sleeper after which the picks are vibrated, creating small movements in the ballast bed which adjusts the position of the individual aggregates to reduce cavities, see Figure 2.10. During the tamping process, the machine is collecting geometric information to the on-board measuring system, which are controlling the gripping devices pulling the rails so that the correct horizontal and vertical position is restored (Esveld (2001)).

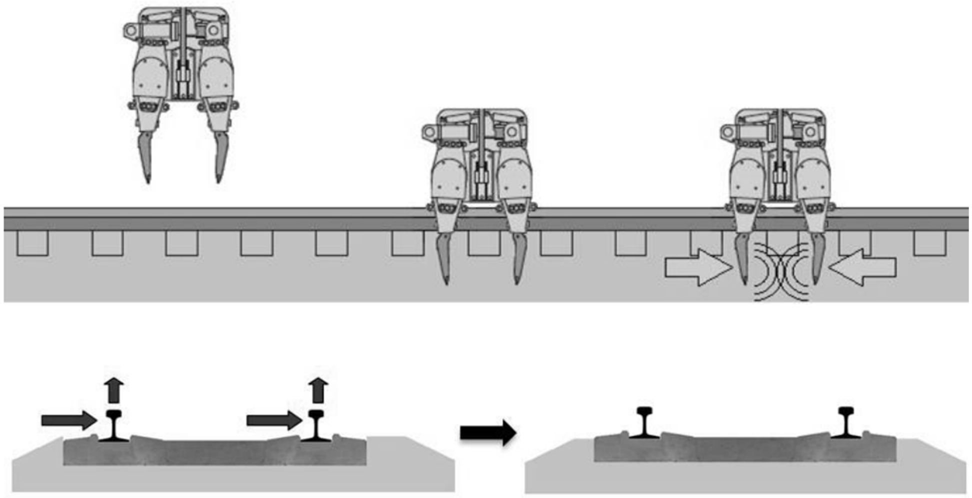

Figure 2.10. Above: Principal sketch of tamping action. Below: The current possition of the sleeper is adjusted horizontally and vertically so the correct position in the cross section is established

Figure 2.11 shows the tamping machine which carries out tamping for plain line in Denmark. Tamping in Denmark is according to railway norm BN1-38-4, 03-12-2010. The table in Figure 2.12 shows the norm for track geometry irregularities of track sections of 200 m. *Fejlkasse* in the table mean track defect classes. Different defect class requires different maintenance actions as shown below,

- Class 0: Permissible variation of tolerances after finishing activities in renewals/ new projects
- Class 1: Permissible variations of tolerances after maintenance
- Class 3: Error to be planned for correction before they may develop to an error in class 4
- Class 4: Errors exceeding this limiting value must be evaluated before 3 weeks if V $>$ 160 km/h and before 6 weeks if V $\leq$ 160 km/h. Time for correction must be planned so the errors should not develop to an error in class Max/Min. The error

Figure 2.11. Tamping machine for plain line (Nielsen (2013))

must always be corrected within 3 month if V > 160 km/h and before 6 month if V ≤ 160 km/h.

- Class Max/Min: Errors exceeding this limit require action to reduce risk of derailment (Close the line, speed restrictions or immediately repair, as further described in the Standard).

In Banedanmark, preventive condition-based maintenance is scheduled when track geometry develops in the range between track defect Class 3 and track defect Class 4 (see Figure 2.12); Corrective maintenance is trigged by track defect Class 4 and above for track spots (see Figure 2.13).

Figur 11.4-1. Normer for **standardafvigelse** i *højde- og sideretning* for sporafsnit à 200 m, **ved anvendelse af målevogn/-dræsine**

Kvalitets-klasse	Hastighed [Km/h]	Højderetning (σ_H) λ=3-25 m		Sideretning (σ_P) λ=3-25 m	
		Middellinje til spids [mm]		Middellinje til spids [mm]	
		Fejlklasse 3		Fejlklasse 3	
		Spor ekskl. sporskifter	Spor inkl. sporskifter	Spor ekskl. sporskifter	Spor inkl. sporskifter
A1	200<V≤250	0,80x	1,00x	0,70y	0,70y
A	160<V≤200	0,95x	1,20x [1)]	0,80y	0,80y
B	120<V≤160	1,10x	1,40x [1)]	1,00y	1,00y
C	80<V≤120	1,40x	1,80x	1,20y	1,20y
D	40<V≤80	1,80x	2,30x	1,50y	1,50y
E	V≤40	1,80x	2,30x	1,50y	1,50y
S					

Figure 2.12. Norms for irregularities of track secton of 200 meters (Rail Standard BN1-38-4 (2011))

Figur 11.3.2-2. Normer for **punktfejl** vedr. *højderetning, sideretning og sporvidde,* **ved anvendelse af målevogn/-dræsine**

Kva-litets klas-se	Hastighed	Højderetning 7) λ=3-25 m					Sideretning 7) λ=3-25 m					Højderetning & Sideretning λ=25-70m			Sporvidde Punktfejl 4)					Sporvidde middel målt over 100 m	
	[Km/h]	Middellinje til spids [mm]					Middellinje til spids [mm]					Middellinje til spids[mm]			1435 5,10) til spids [mm]					1435 til spids [mm]	
		Fejlklasse					Fejlklasse					Fejlklasse			Fejlklasse					Fejlklasse	
		0	1	3	4	Max	0	1	3	4	Max	3	4	Max	0	1	3	4	Max/Min	3	Min
A1	200<V≤250	2,0x	3,0x	6x	7x	10x	2,0y	3,0y	4y	5y	8y	6	12	20	±2	+4/-2	+10/-3	+10/-3	+28/-5	-2 6)	-2 6)
A	160<V≤200	2,0x	3,0x	6x	8x	12x	2,0y	3,0y	4y	6y	9y	9	16	24	±2	+5/-2 9)	+12/-5	+15/-5	+28/-7	-5	-5
B	120<V≤160	3,0x	3,5x	7x	9x	13x	2,0y	3,5y	6y	8y	10y	11			±2	+5/-2 9)	+15/-6	+20/-6	+35/-8	-5	-5
C	80<V≤120	3,0x	3,5x	8x	10x	16x	2,0y	3,5y	7y	9y	13y	12			±3	+5/-3	+15/-7	+25/-7	+35/-9	-5	-5
D	40<V≤80	4,0x	5,0x	10x	12x	21x	3,5y	5,0y	9y	11y	18y	15			±3	+7/-3	+20/-7	+30/-7	+35/-9	-5	-5
E	V≤40	4,0x	5,0x	10x	15x	31x	3,5y	5,0y	10y	12y	25y 8)				±3	+7/-3	+20/-7	+30/-7	+35/-9		
S		4,0x	5,0x	10x	15x	31x	3,5y	5,0y	10y	12y	25y 8)				±3	+7/-3	+25/-7	+33/-7	+35/-9		

Figure 2.13. Norms for irregularities of track spot (Rail Standard BN1-38-4 (2011))

2.4 Planning practices and challenges

2.4.1 Planning practices at Banedanmark

Today, universal measuring car inspects four times a year for the main lines in Denmark. It collects data for permanent railway tracks for every 25 cm. The condition data of the track are stored in so called IRISSYS (International Railway Inspection and Services System) since 2009. The infrastructure data includes traffic loads, asset data (installation dates, component type etc.), designed geometry, rail wear survey results, Geometry survey results and geometry inertial forecast. The geometrical track quality control is conducted to supervise the tracks relative position to the designed geometry which complies with the European standard EN13848-1 and EN13848-2 annex C (Jensen (2013)). The inspections include the measurements for

- Track gauge
- Cant
- Twist
- Standard deviation of sequential measurements for longitudinal and
- Standard deviation of sequential measurements for horizontal alignments.

For the preventive condition-based tamping (mentioned as preventive tamping), tracks are divided into track sections of 200 m each. The track irregularities are provided by the standard deviation calculated from the survey results. Historical experiences at BDK show that more than 90% of preventive tamping were caused by longitudinal and horizontal geometry irregularities in the wave length interval D1 (λ = 3-25 m) (Jensen (2013)). The preventive tamping operation is scheduled once a year for a certain railway corridor. A double track corridor is scheduled as two separated projects of each track. The tamping plan is scheduled by 'Teknisk Drift' department at Banedanmark. The tamping plan is scheduled based on the technical condition-based principal where a tamping is trigged by track irregularity status/forecasts comparing to the thresholds of track defect Class 3. Some economic factors such as yearly budget, priority of the railway corridor, are considered. No mathematical models have been implemented in practice yet.

2.4.2 The current planning challenges

There are many challenges for the current preventive tamping planning:

1. Budget and the track possession for preventive tamping are always limited. The limited budget is not able to cover all the tamping requirements. In practices, money is often running out after tamping the most important track sections on the main lines.

2. Tamping is a complex and critical task which is particularly difficult to plan and execute (Chu and Chen (2012)). It involves rail traffic information, asset status, track possessions, machine planning and budgets etc. It takes long time and many resources to handle the planning.

3. The prediction of track degradation over time is difficult. Track geometries can be impacted by many factors (see Table 2.1). It is hard to ensure the track condition not exceed the thresholds in the planning horizon.

4. There exist operational limitations. Among other things, a tamping machine has a limitation that it is not allowed to start/stop in a transition curve according to tamping norm. Figure 2.14 shows a tamping example. If a tamping section stops inside a transition curve, it requires the tamping operation to extend.

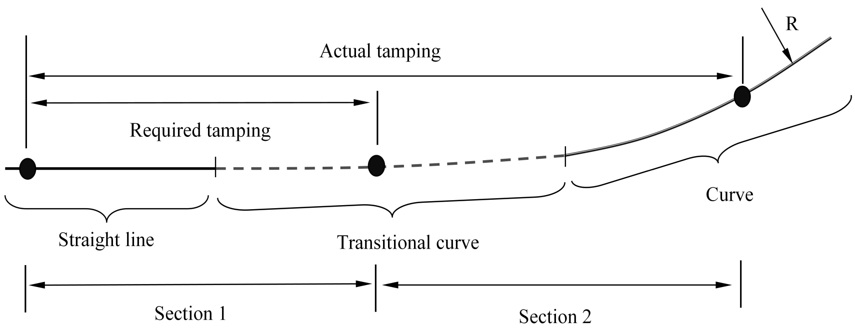

Figure 2.14. Tamping extension on a transition curve (Wen et al. (2016))

5. Preventive tamping is mainly trigged by both the Standard deviation of longitudinal and horizontal alignments. A tamping should be scheduled for a track section when any of them is exceeding the corresponding thresholds. This increases the planning difficult to track the decisions.

6. The current planning method from literature lacks the functionality for expert adjustments, which is as equally important as the computer method for scheduling

tamping. The expert experiences are necessary to ensure the feasibility of the computer generated solution, especially to balance the factors which are not formulated into the model.

2.4.3 Main idea to solve planning challenges

The main idea to solve the planning challenges in the previous section is to implement an asset degradation model to predict track condition. Instead of triggering tamping by track threshold, the proposed method in this thesis guarantees that the thresholds are never exceeded. The difference is that a preventive tamping could be shifted to an earlier date before reaching the threshold in the new method. The advantage of the proposed method is that it is possible to group the maintenance task from space-time dimensions. Even though the cost for a certain track section could increase because an early tamping might cause an additional tamping. But the overall cost can be saved by the grouping (scale of economy). Following this idea, optimization models are formulated to seek the less expensive solutions in this study.

Paper 1 and Paper 2 are carried out for Railway Preventive Condition-Based Tamping Scheduling Problem (RPCBTSP). In Paper 1, a mixed integer linear programming model is formulated and tested on a Danish railway corridor between Odense and Fredericia. The planning challenges (1, 3, 4) from the previous section can be solved. In Paper 2, a Phase-based Decision Support System (PDSS) is introduced to support the railway infrastructure managers to seek the most suitable preventive tamping schedule. The PDSS is formulated in three phases to solve the planning complexities. All six planning challenges can be solved.

Chapter 3

PHASE-BASED DECISION SUPPORT SYSTEM

This chapter introduces the phase-based planning approach and how to use such an approach to solve railway infrastructure scheduling problems and reduce costs. Two types of proposed phase-based planning approaches are described.

The structure of this chapter is organized as follows. Firstly, Section 3.1 demonstrates the complexity of railway planning. Secondly, Section3.2 presents an idea for an efficient planning method by building a generic framework. Then Section 3.3 explains two types of phased-based planning approaches proposed by this study. Moreover, Section 3.4 explains the reason why a phase-based approach can improve the traditional scheduling approaches. Section 3.5 introduces a life cycle cost framework, which gives an overview on the related costs from a extended scope than the traditional way. Lastly, Section 3.6 presents the proposed phase-based decision support systems.

3.1 Complexity Of Railway Infrastructure

Modern railway infrastructure is a complex system. Figure 3.1 shows the links among four sub-systems and the links to the outside world. The purpose of showing them is to illustrate that any system changes related to one sub-system can impact the others: Therefore, railway planning is a complex task. Let's use a Danish example, Ringsted-Fehmarn Banen (RFB) project, to illustrate the complexity of the planning for a big scale railway project. This railway project contains four main tasks, i.e.

- Upgrading the railway maximum speed to 200 km/h,
- Expanding the current single track line to a double track line,
- Electrifying the line and
- Upgrading the signalling system.

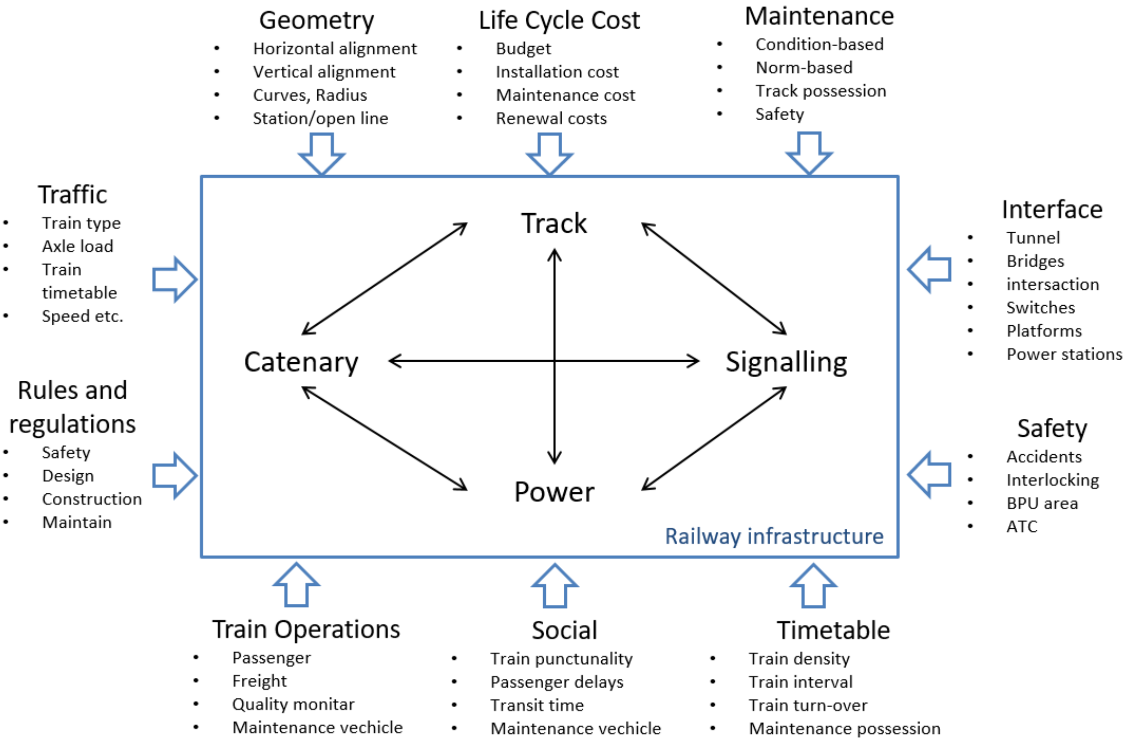

Figure 3.1. Railway infrastructure subsystem relations and their links to outside world

There will be 102 bridges to extend, approximate 1.2 million tons soil to handle, about 900,000 tons new materials to use and 60 km of new railway to construct and many other tasks (de-watering, signalling, roads etc.). A design for a single change, for example, extending a current bridge for carrying the future double track will involve the design work for the other three subsystems (catenary system, interlocking system, and power supply), too. The upgrade costs, future maintenance procedure, railway safety, track possession, train timetables and many other things as demonstrated in Figure 3.1 will be impacted by an implementation plan.

A good plan needs,

- Reduce the inconvenience to passengers
- Ensure maximum "return of money"
- Ensure a robust timetable
- Reduce the changes in the existing signalling system as much as possible, and
- Ensure a schedule that is attractive for contractors

An efficient planning method is therefore needed to dill with the complexity and find such a good plan. The next sections will introduce how this study approached the proposed phase-based planning methods.

3.2 A Framework For Planning

The first idea for an efficient planning method is to build a generic framework, get focuses and solve the planning challenges step by step in a systematic approach. The method should be in steps because there are far too many things to consider. Those things are also linked to the others at the same time. Without focusing and prioritizing, it could turn to a no-ending planning.

A framework illustrated in Figure 3.2 shows the focus areas prioritized by this study. The green boxes indicate the topics covered by this study. The red boxes are the topics suggested for future research. And the black boxes are not the focuses in this study. Moreover, this thesis covers the maintenance planning at the primary planning level. Staff scheduling problem, maintenance vehicle routing problem and material supply and disposal, for the detail maintenance plan, are not included in this study. The objective is to propose an efficient planning method to seek good maintenance plans based on the common factors at the high level planning level.

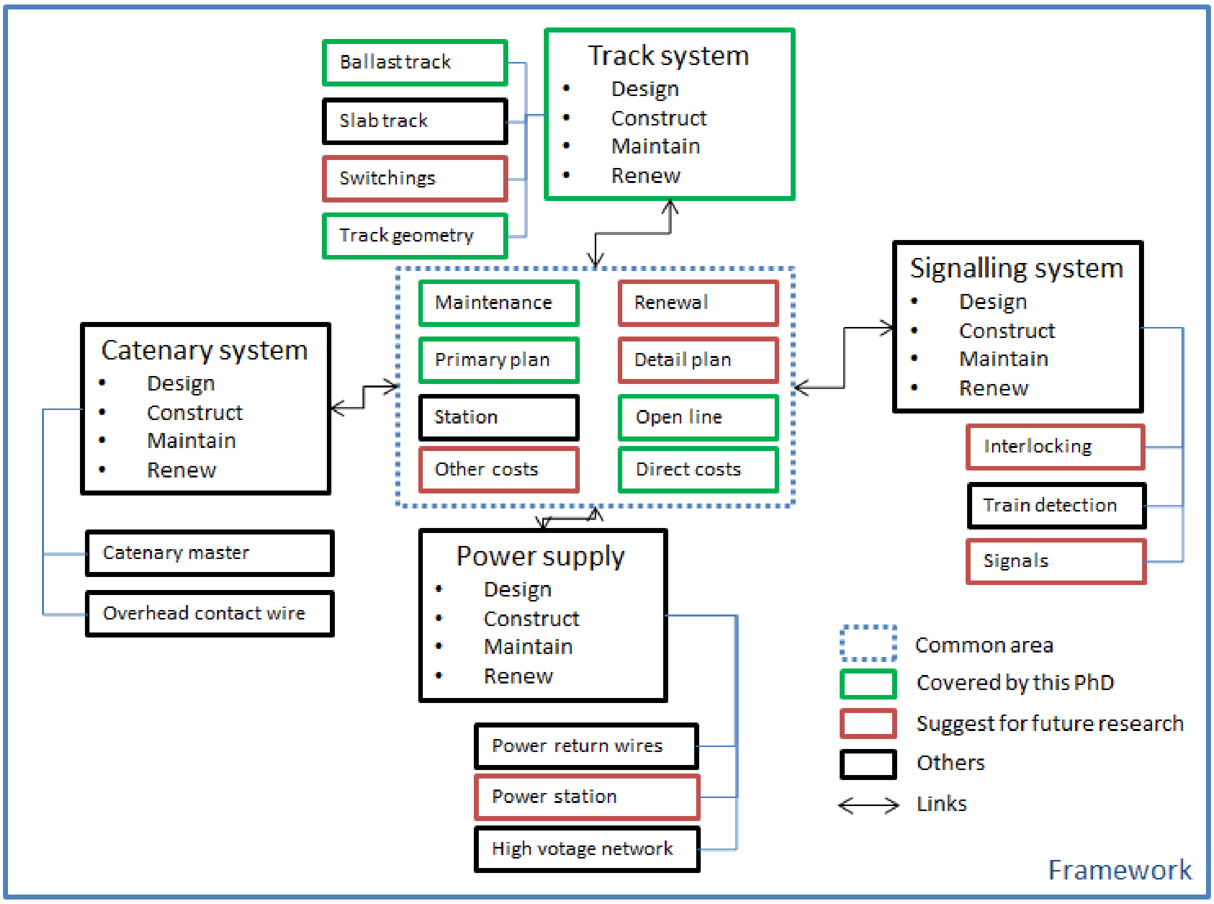

Figure 3.2. A framework of the planning area for this study

Additionally, direct cost has been set as focus in Papers 1-3 because it is the money directly from infrastructure managers. As a key performance indicator, it is continuously measured and budgeted in real practices. Other costs covered in Life Cycle Costs, see Section 3.5 and Paper 4, are not standardized in practice so far and therefore not included in Papers 1-3.

At last, open line between stations has been chosen to reduce the planning complexity, especially for the preventive condition-based tamping scheduling problem. The tamping scheduling for stations are often planned according to the layout and the interlocking system case by case. An applicable planning method for one station is often not applicable for another.

3.3 Phase-Based Planning Approach

Phase-based planning is a planning approach contains multiply phases to plan railway projects. Phase-based planning is not new in the railway fields and it has been often mentioned in railway conferences (Rambøll (2012), Madsen et al. (2014), Zoeteman (2001), Zoeteman (2006)). However, the concept of phase-based planning approach and the definition of the included planning phases are different from time to time.

Phase-based planning approach can be grouped into two main types based on the output solutions:

1. Process-Oriented Phase-Based Planning Approach (PO-PBPA), in which one output solution (typically a cost-benefit analysis) can be generated through the included phases. In PO-PBPA, each phase calculates only certain parts of cost-benefit. A total cost-benefit value can be estimated through the relevant phases.

2. Functional Phase-Based Planning Approach (F-PBPA), in which several output solutions are generated based on the defined functions. In F-PBPA, each phase generates one or several overall solutions based on the defined function in the phase.

Let's use a renewal project for sleepers as an example. Let's assume that there are three types of sleepers to be compared, wooden sleeper, concrete sleeper and used concreted sleepers. PO-PBPA can estimate an overall Life Cycle Cost (LCC) for each sleeper by estimating installation cost, maintenance cost, and disposal value in three phases. The final decision can be made by comparing the overall costs. Instead, F-PBPA could generate several comparisons, such as a comparison on life span, axle load, and weight, and a comparison on cost, and maybe another comparison on the difficulty of maintenance. The decision making in F-PBPA is not limited by a pure cost-benefit analysis.

Moreover, the definitions of the included phases are also different. In PO-PBPA, the phases are often defined in order of the planning processes. For example, (Zoeteman (2001)) suggests to estimate LCC through the following processes,

- Process 1: Estimating the traffic loads on the infrastructure
- Process 2: Estimating the periodic maintenance volume
- Process 3: Estimating the total maintenance costs and possession hours
- Process 4: Estimating the failure performance
- Process 5: Estimating the life cycle costs

The similar process-oriented approach was used by (Veit (2012)) to plan railway maintenance strategies by comparing railway infrastructure annual costs of the different options. The annual cost was estimated by summing up three types of costs, i.e. yearly depreciation, cost of operating difficulties and maintenance costs. Costs are estimated in separated phases. In Denmark, (Madsen et al. (2014)) introduces another efficient planning method by going through the process-oriented planning phases as follows,

- Ensuring the convenience to passengers
- Ensuring maximum of the return of invested money
- Ensuring the robustness of timetable/track possession
- Ensuring the attractive project schedule for contractors
- Reducing the changes in the existing system (signal, tracks and cables) as much as possible etc.

By using those phases, the final solution in PO-PBPA can also be made not only focusing on costs.

Instead, F-PBPA defines phases according to functions. For example, Banedanmark developed Track Analysis Model (TAM) system to plan track renewals. TAM contains three main functional phases, i.e. Technical degradation model, Economical optimization model and constrained optimization model (Banedanmark (2012b)). The technical degradation model is used to simulate the infrastructure technical ageing processes and estimate when and where to implement renewals for rail, sleepers and ballast from the purely technical point of view. While, the Economical optimization model is to seek a track renewal plan with a lower overall costs. The new plan is achieved by grouping track renewals operations from time and space dimensions based on the output schedule from the technical degradation model. At last, the renewal budget/resources are added in the constrained optimization model to seek alternative feasible solutions.

The phase-based approach in this thesis covers both approaches. Papers 1-3 implement F-PBPA while Papers 4-5 use PO-PBPA. An universal Phase-base Decision Support System (PDSS), proposed in Paper 2, is based on F-PBPA. Three functional optimization phases in PDSS are the same as the ones in TAM. Paper 1 and Paper 3 build one part of the

PDSS to solve different scheduling problems. Paper 1 solve railway preventive condition-based tamping scheduling problem. While Paper 3 solves the railway track possession scheduling problem. Paper 4 and Paper 5 introduce the life cycle cost and propose two planning frameworks, using PO-PBPA, to estimate total cost for railway projects. The main contributions of this study are from Papers 1-3. Without loss of generality, the phase-based approach mentioned in the rest of the chapter refers to F-PBPA.

3.4 Why Phase-Based Approach

There are three main reasons why a phase-based approach can improve the current practices for any infrastructure related planning tasks. 1) Infrastructure maintenance scheduling have to consider multiple impact factors. At the one hand, the purpose of maintenance and renewals is to improve the infrastructure physical status, also called technical status, such as the track geometry irregularities. Thus, technical condition needs to be measured and evaluated all the time; On the other hand, the economic factors such as maintenance costs and budgets are always impacting maintenance schedule. Considering all the impact factors in a mathematical model and giving an optimal solution, as demonstrated in Figure 3.3 (the method on top), result in a limited transparency for Infrastructure Manager (IM) to understand. Only giving a maintenance schedule without giving the reason why scheduling it as a such, is actually not convincing and very hard to evaluate in practice.

Figure 3.3 illustrates a comparison between a typical academic approach and the new phase-based approach, where the transparency for solutions can be improved via phase based approach. The more details are included in Paper 2.

A phase-based approach, referring to the second method in Figure 3.3, gives the maintenance schedule in a logical order. Firstly, it identifies the maintenance needs (where/when to implement maintenance) purely based on the technical degradation, which can be accepted in the practices. Then, it provides a more economical (less costly) maintenance schedule by adding the costs into the optimization objective function. By comparing these two outputs, it is then possible to evaluate the output and therefore the understanding can be improved. Finally, adjusting the solution by other constraints such as budget can achieve more suitable alternative solutions. By going through these phases, the understanding barrier can be overcome. Secondly, the approach, which is not phase-based, lacks the functionality for expert adjustments. In practice, expert adjustments are as equally important as the computer method for scheduling Maintenance. Lastly, as the same as so-called modular design principal, a phase-based method is an approach that subdivides a system into smaller parts (phases), that can be independently created and used. So it becomes easier to customize for different scheduling problems, and easy for future improvements.

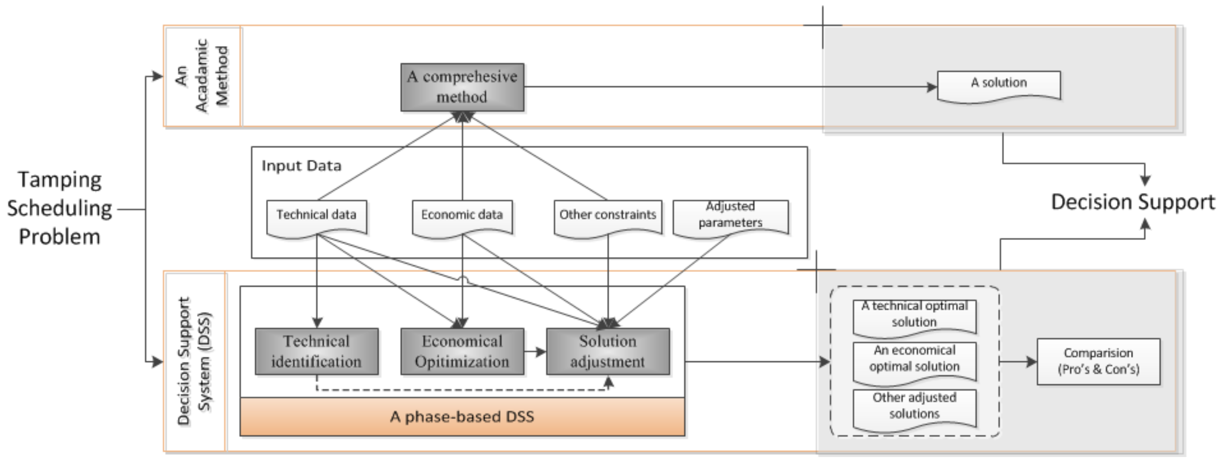

Figure 3.3. Above: A typical academic approach, where all the impacted factors are included in one comprehensive model, from which only one best solution is generated. Below: The Phase-based Decision Support approach, where the input data was divided into technical data, economic data, and other constraints and adjusted parameters. The tamping problem is solved in three optimization phases accordingly. A comparison report with a pool of solutions are generated to support decision-making

3.5 Life Cycle Cost Framework

Life Cycle Cost (LCC) is a main principle of economic investment evaluation. It basically counts all costs from one investment until the next re-investment. LCC becomes more and more popular in evaluating the railway infrastructure project because railway infrastructure components have relative long life spans (Zoeteman (2001), Veit (2012)). Any short term decision is not only deciding the cost at the time period of the decision, but also impacting the railway in a long run. One common example is balancing between railway maintenance and renewals. Too much budget cutting on short term railway maintenance can lead to an increasing track damages in a long run. Thus, it can result in significant increased costs on track repair and more intensive renewals. LCC can help to seek the sweet point for railway Maintenance and renewals (M&R), minimizing the overall track costs.

However, most of the focuses of LCC today are still limited to the direct-costs, i.e. construction, maintenance, renewal costs and disposal values, in the railway fields, because those are the actual expenses that are budgeted, measured and evaluated all the time. The short-sighted LCC could lead to an underestimation on overall costs, because the non-documented costs or unplanned costs, such as train delays, emergent track reparations caused by poor track quality, also have impacts. An extended LCC scope is therefore important to plan the railway long term M&R strategy (Li et al. (2013a)). Figure 3.4 illustrates an extended LCC framework to consider. The details of LCC are presented in Paper 4.

Among the extended LCC framework, Society loss is a social economical cost mainly calculated by passenger delays and train operator's additional costs. Paper 5 uses a case study to illustrate how those indirect costs can impact the railway maintenance decisions.

For the long term planning as mentioned in Papers 4-5, extending the LCC scope could achieve a better estimation on the overall project costs. However, a wider cost scope doesn't suit for any project. The scope has to be made according to the project, such as the project type, the available input, and the computing time etc. For example, Paper 3 in this study plans the track possession for a large scale railway project over five years. Government and authorities want to know the rough cost difference among alternative full-closure options without running the detail calculations, the scope of cost is therefore determined to include the common costs of materials, labor and machinery. Paper 1 and Paper 2 optimize tamping scheduling problem with more practical details. Therefore it includes the cost from a more detailed level.

3.6 Optimization Phases

A Phase-based Decision Support System (PDSS) contains five main phases: 1) Data input 2) Technical Optimization (TeO) 3) Economic Optimization (EcO) 4) Constrained Optimization (CoO) and 5) Analysis and comparison. The optimization phases, i.e. TeO, EcO and CoO, are the cores (Journal Papers 1-3). Mixed Integer Linear Programming models (MILP) are formulated in these three phases for different scheduling problems, respectively. TeO is used to identify the minimum technical maintenance needs from a pure technical perspective. EcO is applied to generate an economical optimal schedule by taking related costs into account. And CoO considers the additional constraints and

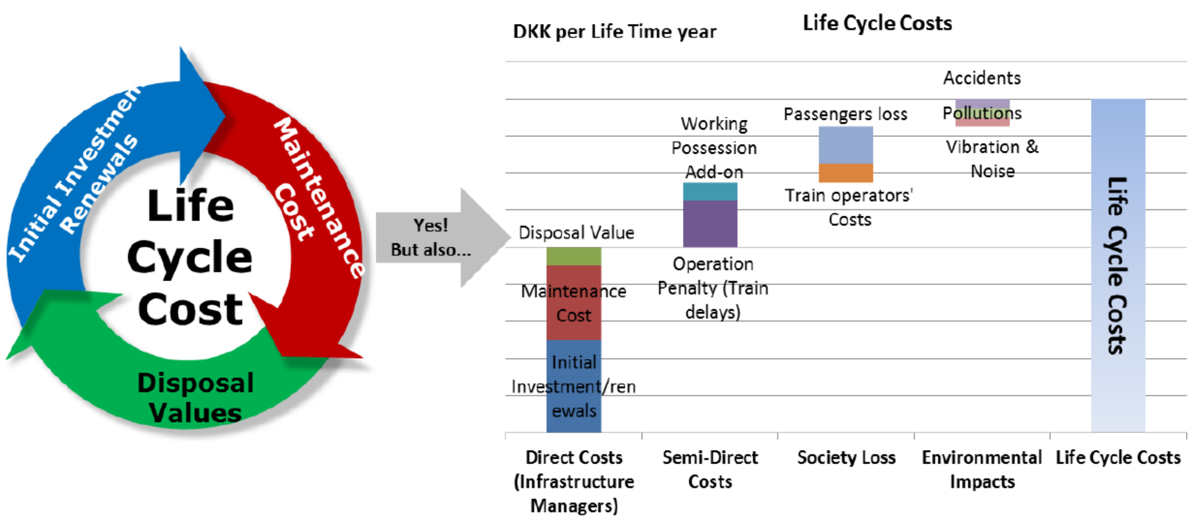

Figure 3.4. The tranditional and the extended Life Cycle Cost Framework

allows the railway experts to adjust the maintenance schedule. Finally, a set of outputs from PDSS can provide decision supports. Figure 3.5 illustrates the particular PDSS for Railway Preventive Condition-Based Tamping Scheduling Problem (RPCBTSP)

In PDSS, TeO, EcO and CoO are ordered according to the planning practices. However, they are actually independent from each other meaning that railway Infrastructure Managers (IMs) have the flexibility to run them in any combination/sequences.

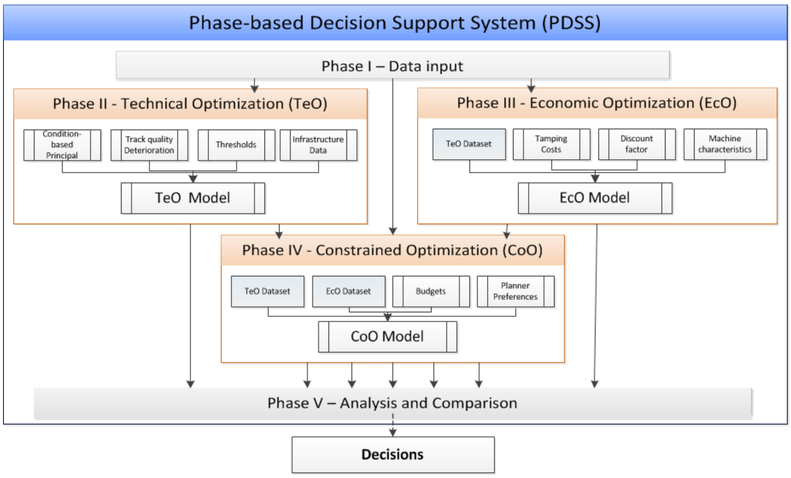

Figure 3.5. A PDSS framework for RPCBTSP

3.6.1 Technical optimization

Technical Optimization (TeO) phase, also called technical degradation model, is used to track the technical degradation status of the track system, which has to be controlled in a physical range according to railway safety (see the TeO model in Paper 2). The tamping operations will be scheduled according to the technical condition-based principal, i.e. when the technical condition of track is reaching the threshold (condition), a tamping is scheduled at the possible latest time period. Tamping cost is not considered in the technical optimization.

Railway Track Possession Scheduling Problem (RTPSP) is not to be solved in TeO because the cost cannot be ignored for choosing track possessions.

3.6.2 Economical optimization

Economical Optimization (EcO) is recommended as the next level optimization after TeO, where the relative cost/price data will be added on top of the technical factors. The aim is to find a maintenance schedule with minimal total cost, while satisfying all the technical constraints in TeO. All the constraints considered in TeO are also included in EcO. In EcO, the tamping are no longer always scheduled on the possible latest time, where the track quality reaching the thresholds as in TeO. Early tamping will be scheduled in order to group tamping and achieve scale of economics, because tamping once every three quarters is often cheaper than tamping three times (tamping every quarter). See the EcO model in Paper 2 for the RPCBTSP.

Figure 3.6 demonstrates the inputs and outputs in EcO.

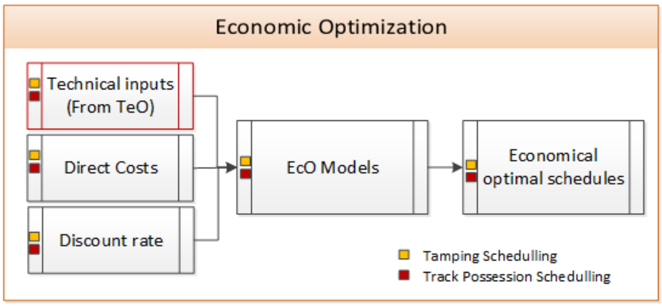

Figure 3.6. Inputs and outputs for EcO phase

3.6.3 Constrained optimization

Constrained Optimization (CoO) is an extension of EcO, where additional constraints are added to adjust the economical optimal schedule. Budget, resource constraints and planner preferences are the practical constraints to consider. In this phase, railway experts can also set the preferred time periods for tamping. It's done by reducing the fixed track possession cost for the preferred time, so the CoO model has tendency to choose them. Infrastructure Managers (IMs) have more flexibilities in CoO. The outputs from CoO could be used as alternative scenarios to support the final decision. Figure 3.7 shows the processes in CoO. The disadvantages, however are 1) there does not always exist a feasible solution within newly given restrictions, 2) the total cost could increase compared to the EcO and, 3) longer computing time should be expected.

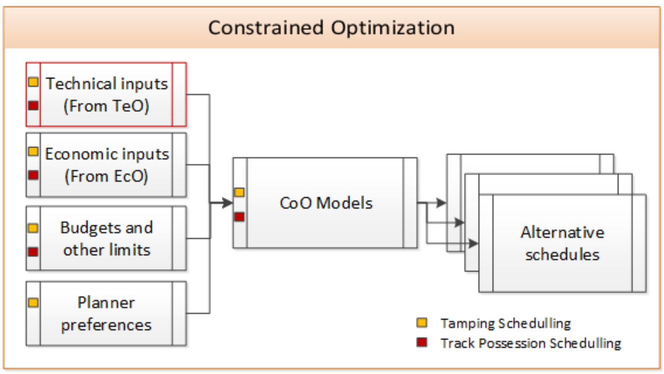

Figure 3.7. Inputs and outputs for CoO phase

See the CoO Model in Paper 2 for the detailed formulation for RPCBTSP. The model presented in Paper 3 contains technical, economic factors and many adjustment constraints. It can be seen as the CoO model for RTPSP.

3.6.4 Applications of operations research

This study solves two railway scheduling problem by using Operations Research. MILP models are formulated in the three optimization phases in PDSS for each scheduling problem. MILP models are solved by IBM ILOG CPLEX version 12.6.0.0. The computing results are to be presented under each schedule problem in the attached Papers 1-3.

The results show that, in two hours of computing time, the proposed MILP models are able to provide solutions that are within 2% gap from the optimal (see Paper 3 for more explanation about the gap from the optimal). The overall cost saving can be up to 40% comparing to the literature (Papers 1-2) and the current practices (Paper 3).

Chapter 4

DISCUSSION

This chapter is to describe the strength and weakness of the proposed planning methods, and discuss how to use those methods to improve the current railway planning practices.

4.1 The Advantages Of Strategic Planning

Strategic planning is to plan railway projects at the primary planning stage and only involving the common/average information. Comparing to the other two levels, i.e. tactical level and operational level, the planning horizon for strategic planning is longer. Meanwhile, operational planning needs involve all the necessary details for a particular project, and tactical planning is in between, see Table 4.1.

Table 4.1. Planning Levels

Level	planning horizon	Details
Strategic planning	Long term	High level (Common machine, average costs etc.)
Tactical planning	Middle term	Middle level (particular machine type, machine routing)
Operational planning	Short term	Very detailed (Resource plan, task management and detailed time schedule etc.)

It is beneficial to implement strategic planning for railway infrastructure project because of the following advantages, *Strategic planning has a longer planning horizon. It could achieve a better economy than short term planning*

In general, strategic planning focuses on a long term scheduling could help to get a long term overview and reduce costs. Just like “global” optimization vs. “local” optimizations, where a “global” optimization could find a project plan with overall minimum total cost instead of summing up multiply “local” optimizations of the subsets of the planning horizon.

Papers 2 has presented a comparison between long term planning and short term planning for RPCBTSP in a Danish case study. It shows that the cost savings, obtained by prolonging the planning horizon from 1 year to 2 years, from 1 year to 3 years, are 11% and 15%, respectively. The longer the planning horizon, the more options to group tamping, and the better economy. However, the main disadvantages are: 1) the accuracy of the forecast of track behaviour drops over time and 2) computing time increases exponentially.

The solution is much more controllable on the long term than it is on the short term

It means that the maintenance has flexibilities to move to other periods in the long term plan while the short term doesn’t really have many choices. Paper 2 describe the challenges of the existing planning for the RPCBTSP in practice, that infrastructure managers planing tamping in a short term horizon. They have very limited options to group tamping to achieve a better economy. This can be improved by a long term planning with an degradation model to predict track condition as proposed in Papers 1-2.

Strategic planning doesn’t have to involve too many details. It could be used to filter out a short-list from large amount of alternatives at an early stage.

Strategic planning could get a cost overview for a certain solution quickly with only considering the common factors. The government and authorities often need to make strategical decision before the project team working on the detail planning, which takes a longer time to do. The rough estimation is important to get few options from a large amount of possible options. So the short list can be used by the project team to calculate details for the final decision.

Paper 3 presents such a scheduling model for track possession scheduling problem. The case study from the Danish Ringsted-Fehmarn railway upgrading project shows that the proposed model could get a cost estimation within two hours. It is then possible to extend the base of the alternatives.

However, strategical planning itself costs money and resource. It is often defined as "Nice-to-have" comparing to "Must-to-have" for the operational planning. When the railway budget is too tight or the country's economy is not running well, strategical planning is always the first function to be cancelled in the past. This study has tried to highlight the importance and the cost-savings that could be achieved by the strategical planning. The writer hopes that it can be recognized by the railway management so that more funds and resources could be invested into this area.

4.2 The Strength Of Phase-Based Approach

Phase-based planning method is a systematic approach to solve the scheduling problem step by step. Building up a functional phase-based decision system could encourage railway infrastructure manager to understand and implement research results.

Solving a maintenance scheduling problem from the technical perspective, the economical perspective, and the operational perspective in sequence, could divide a complex problem into solvable sub problems. Visualizing the solutions from different perspectives could help infrastructure managers to understand computing models.

Paper 2 proposes a functional phase-based planning approach. Visualizing the outputs from the technical, economical and constrained optimization phases can help infrastructure managers to understand where and when the preventive maintenance are technically needed, how to schedule the tamping covering those needs in a most cost-effective way. It can be more convincing for them to use computing models.

A phase-based planning approach could estimate the total cost from a wider Life Cycle Cost perspective. It is suggested to take other important costs, such as passenger delay, into consideration at a early stage.

Paper 4 introduces a wide Life Cycle Cost framework and a Process-Oriented Phase-Based Planning Approach to estimate the overall railway project cost. Paper 5 illustrates how the wider cost framework influences the current railway project decisions. A case study in Paper 5 illustrates that the track possession choice might change by taking passenger loss into cost estimation at the early stage.

A phase-based system can be customized for a certain planning problems, and easier for maintenance and future improvements.

Railway projects don't have to consider everything for cost estimation. It depends on the project scope, the available data and the limited resources. A phase-based system is easier to customize by selecting the related phases and de-selecting the others. Each phase can also be maintained and improved separately without changing the entire decision support system. Therefore, it can be easier to maintain and upgrade.

4.3 The Importance Of Setting Budget In An Appropriate Range

Running a railway project often requires infrastructure managers to carefully plan and review their financials. Budgeting is probably one of the most important accounting tools widely used. For a railway infrastructure maintenance project, setting a fixed period budget could prevent cost overrun. However,

Setting a period budget can increase overall maintenance cost.

When the budget is set too tight, it is against maintenance grouping (*scale of economy*). The tight budget is not allowed to implement many maintenance at one certain period. Therefore, some of them have to distribute to each periods resulting in an increased costs. The analysis in Paper 2 concludes that total expenditure rises exponentially with the reduction of the period budget. The paper recommends an appropriate range for setting budget to balance the cost overrun risks and potential increased costs caused by budget.

4.4 The Sensitivities of Impact Factors

Paper 3 introduces the track possession scheduling problem and concluded that the weight among labor, machine and materials can impact the track possession decision choosing among night, daytime interval, weekend and full-closure track possessions,

For the railway task which is labor and machinery dominated, it is crucial to calculate the costs and wisely choose among track possessions. When the unit cost of a task is dominated by material cost, it can choose the track possession with minimum interruption to the existing railway services, such as night possession.

Labor and machine costs grow dramatically in the night and weekend track possessions. It is therefore better to find the period when the track can be fully closed to implement for the tasks which are labor and machinery dominated, such as dam extensions. Because executing them in the other track possessions will cost double or even treble times more. On the opposite, when the task contains not so much labor and machine costs (materials is dominated) such as replacing rails, install new switches. It is better to use night possessions, because the potential loss for passengers caused by the interruption to the existing railway services can be reduced with a slightly increased installation cost at nights.

To plan preventive tamping, it is important to consider tamping machine driving speed, tamping speed, preparation and ramp down time instead of only consider the number of tamping sections. The schedule obtained by minimizing the number of tamping operations is more expensive than the schedule considering tamping machine characters.

Paper 1 analyses the sensitivity of tamping machine parameters for RPCBTSP and concludes that it is beneficial to implement continues tamping for three continuous track sections even the middle track session might not need a tamping. It reduced the time for tamping machine ramping up/down and therefore improve the working efficiency and also save cost.

The tracks degradation rate increases will lead to a linearly climbed condition-based tamping work. It is necessary to add a buffer value to the fixed track degradation rate to schedule tamping in practice, ensuring a full coverage of the tamping needs.

The proposed models in Papers 1-2 only support a linear track degradation. However, track quality can degrades faster and faster for certain sections (Veit (2006), Veit (2012)). Additional tamping could suddenly offset the savings presented from the proposed PDSS. Paper 2 discusses the sensitivity of track degradation rate and concludes that a buffer should be added on top of the estimated track degradation to ensure a full coverage of the tamping needs. Meanwhile, a frequent track quality survey and continuous tamping schedule adjustment are also necessary to supplement a sound preventive tamping strategy.

4.5 The Importance Of Life Cycle Cost

During the planning of railway infrastructure projects, Infrastructure managers have to make many decisions, such as choosing the infrastructure component and deciding the maintenance and renewals.

Considering a railway infrastructure project from the life cycle cost point of view could help infrastructure manger to open eyes to the asset entire life time. Comparison on the annuity of alternatives can help to reduce long term costs.

Life Cycle Cost can help to evaluate alternative proposals and identify the overall cost-efficient solutions (Zoeteman (2001). Paper 4 and 5 introduce a LCC framework evaluating the project options from a larger scope. The project's key evaluation indicators such as track quality, LCC annuity, Cash flow and accumulated NPV curve over years, can be visualized to support the comparison.

Chapter 5

THESIS CONTRIBUTION

The thesis is funded by "the Danish Railway Sector Association" (BaneBranchen in Danish). The contributions of the thesis are both methodological and computational. In the following, major contributions of the thesis are first highlighted, then the contributions along with each attached papers are presented.

The thesis has the following major contributions:

- Providing a method of a Phase-based Decision Support System (PDSS) that is able to solve multiple railway scheduling problems in a systematic process.
- Improving knowledge (new formulations) on the Railway Preventive Condition-Based Tamping Scheduling Problem and obtaining cost reduction compared to the existing literature.
- Defining a new Track Possession Scheduling Problem (RTPSP) to provide decision support in Large-scale projects with multiple construction works at the primary planning level.
- Providing a framework of Life Cycle Cost and a phase-based process to support cost estimation in railway infrastructure projects.
- Integrating passenger loss into cost estimation for railway renewal projects and illustrating how it impacts the track possession decisions.

The outline of the thesis with detailed contributions of each paper are now explained.

Paper 1, **Optimization of preventive condition-based tamping for railway tracks** presents the Railway Preventive Condition-Based Tamping Scheduling Problem (RPCBTSP), which is applied on the railway tracks to correct the standard deviation of the longitudinal level for safety and comfort of passengers and freight. Previous studies have shown that optimizing tamping activities can lead to substantial savings in maintenance costs (Grimes and Barkan (2006), Macke and Higuchi (2007), Uzarski and Mcneil (1994), Vale and Lurdes (2013), Wagner et al. (1964), Chu and Chen (2012), Oyama and Miwa (2003)). We study the available literature (Vale et al. (2012)) and improved OR model by considering a number of practical issues such as extra practical cost components (preparation cost and driving cost), the time value for costs (through net present value) and a more realistic estimation of the tamping recovery (new recovery constraints). As a result of testing on real-life data collected from the Danish railway corridor between Odense and Frederica, the computational results show that it is important to consider extra cost components as they account for half of the total cost. The schedule obtained by minimizing the number of tamping operation is in fact 59% more expensive than the schedule given by minimizing the total cost.

We estimate the tamping recovery based on both the current track quality and the impact of previous tamping operations, which has been proven relevant (Caetano and Teixeira (2014), Chang et al. (2010), Ferreira and Murray (1997), Quiroga and Schnieder (2012), UIC (2008), Zoeteman (2006)) and leads to a more realistic estimation. The case also shows that without the extra constrains on the tamping recovery, the total cost is under estimated by up to 10 %. By minimizing the Net Present Value (NPC), unnecessary early tamping operations are avoided and the final track quality at the end of the planning horizon is improved by 2% without extra cost.

We believe that this paper is a positive step towards finding the least-cost and realistically tamping plan for RPCBTSP. The work has been disseminated as follows:

- Min Wen, Rui Li, Kim Bang Salling, "Optimization of preventive condition-based tamping for railway tracks", *European Journal of Operational Research*, 2016, Vol. 252, Issue 2, pp. 455 - 465, *published* (Wen et al. (2016))

- Rui Li, Kim Bang Salling, Arjen Zoeteman, A.R.M. Wolfert, "Preventive condition-based tamping for railway tracks: a decision support model", *International Symposium on Life-Cycle Civil Engineering (IALCCE)*, 2016, Delft, the Netherlands, *invited, presented and published* (Li et al. (2016))

- Rui Li, Min Wen, Kim Bang Salling, "Optimal Tamping for Railway Tracks - Reducing Railway Maintenance Expenditures by the Use of Integer Programming", *The 17th International Conference on Railway Engineering and Management (ICEAM)*, 2015, Copenhagen, Denmark, *presented* (Li et al. (2015b))

- Rui Li, Min Wen, Kim Bang Salling, Alex Landex, Steen Nørbæk Madsen, "A Predictive Maintenance Model for Railway Tracks Integer program to optimize condition-based tamping", *International Congress on Advanced Railway Engineering (IC-ARE)*, 2015, Istanbul, Turkey, *presented and published* (Li et al. (2015c))

Paper 2, **a phase-based decision support system for railway preventive condition-based tamping** presents a concept of a Phase-based Decision Support System (PDSS) that is able to solve RPCBTSP in a systematic phase-based process. The proposed PDSS contains five main phases: the data input phase, the Technical Optimization phase (TeO), the Economic Optimization phase (EcO), the Constrained Optimization phase (CoO), and the analysis and comparison phase, illustrated in Figure 5.1.

Three new Mixed Integer Linear Programming (MILP) models have been formulated to optimize tamping solutions from different perspectives in TeO, EcO and CoO phases. The TeO is used to identify the minimum tamping needs from a pure technical perspective. The EcO is applied to generate an optimal tamping schedule with the minimum total cost by taking related costs into account. And the CoO considers the additional static budget, the rolling budget and the planner preferences constraints to prove more realistically tamping alternative solutions.

In the mathematical models of the PDSS, two geometry indicators, the standard deviation of longitudinal level defects and the standard deviation of horizontal alignment defects, were monitored simultaneously. As a result of a real Danish case study, the detection of tamping requirements were improved with up to 6% and therefore the new models can strengthen the track quality control. Furthermore, the analysis of the results suggest a long term planning to reduce total cost.

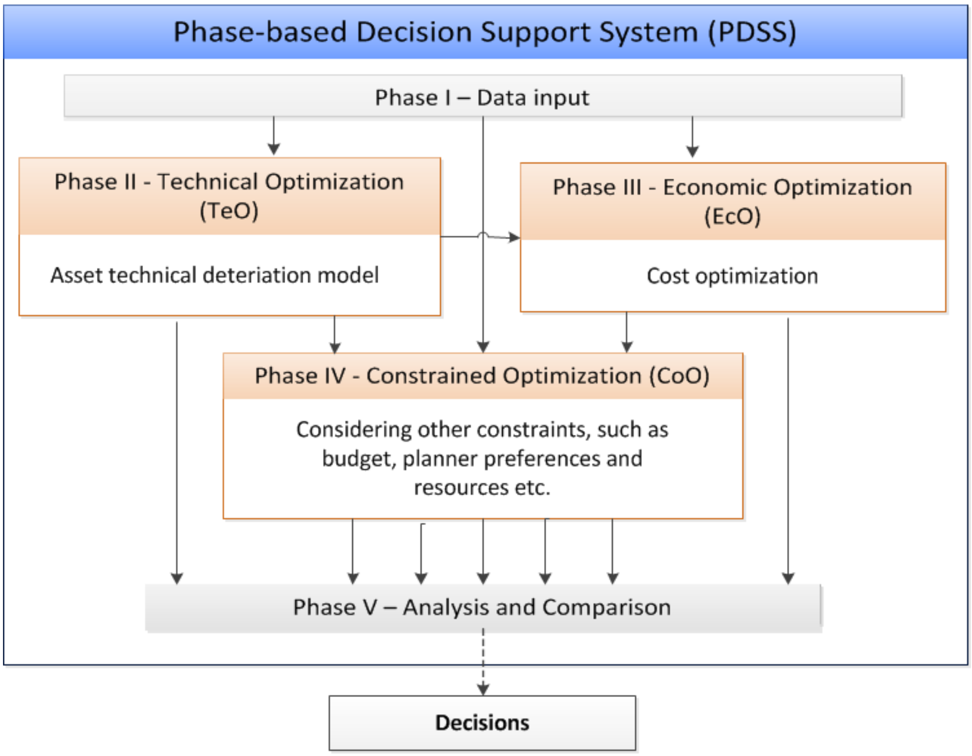

Figure 5.1. Phase-based Decision Support System

A phase-based mathematical programming approach such as the proposed PDSS, has great potential to support the preventive tamping decisions in the real world. The work has been disseminated as follows:

- Rui Li, Min Wen, Kim Bang Salling, "A phase-based decision support system for railway preventive condition-based tamping", *European Journal of Transport and Infrastructure Research, Submitted* (Li et al. (2017))

Paper 3, **Optimal Scheduling of Railway Track Possessions in Large-Scale Projects with Multiple Construction-Works** presents the Railway Track Possession Scheduling Problem (RTPSP), where a large-scale railway infrastructure project consisting of multiple construction works is to be planned. The RTPSP is to determine when to perform the construction works and in which track possessions while satisfying different operational constraints and minimizing the total construction cost. The RTPSP is new problem which has not been defined in literature. The proposed mathematical models are based on the current Excel-based calculation from a railway consult company Rambøll Denmark (Rambøll (2011)).

To find an optimal solution of the RTPSP, this paper proposes an approach that, first, transfers the nominal market prices into track-possession-based real prices, and then generates a schedule of the construction works by solving a MILP model for the given track blocking proposal. The proposed approach is tested on a real-life case study on a Danish railway corridor. The results show that, in 2 hours of computing time, the approach is able to provide solutions that are within 0.37% of the optimal one for six different blocking proposals and two alternative construction providers, so it can be used as an effective support tool in the primary planning stage to suggest preferable track possessions within the existing railway services. The work has been disseminated as follows:

- Rui Li, Roberto Roberti, "Optimal Scheduling of Railway Track Possessions in Large-Scale Projects with Multiple Construction-Works", *Journal of Construction Engineering and Management*, 2017, Vol. 143, Issue 2, (Li and Roberti (2017))
- Rui Li, Alex Landex, Steen Nørbæk. Madsen, "Efficient Planning", *The Danish railway conference (Danish Den Danske Bane Konference)*, 2015, Copenhagen, Denmark, presented (Madsen et al. (2014))
- Rui Li, Alex Landex, Steen Nørbæk Madsen, Otto Anker Nielsen, "Estimating railway infrastructure project cost from transferring nominal price to real price by considering the working time possessions", *Computers in Railways (COMPRAIL)*, 2014, Rome, Italy, *published* (Li et al. (2015a))

Paper 4, **A Framework for Railway Phase-based Planning** introduces a phase-based framework to guide the cost estimation of railway maintenance and renewal projects at strategic level. The framework evaluates the project options from a larger Life Cycle

Cost (LCC) scope: not only considering direct costs but also indirect costs such as social economical costs.

The paper proposes a phase-based processes to estimate total cost. The project's key indicators such as track quality and life time, the LCC annuity, Cash flow and Cumulated NPV curve over years, are visualized to compare among alternative proposals. A case study is introduced to demonstrate the usage of the phase-based method by comparing timber sleepers and concrete sleepers for a railway renewal project.

The new LCC framework tries to open mind, considering not only the costs from infrastructure managers own perspective but also from train operators, passengers and government's perspectives. The work has been disseminated as follows:

- Rui Li, Alex Landex, Steen Nørbæk Madsen, Otto Anker Nielsen, "Framework for Railway Phase-based Planning", *Trafikdage*, 2013, Aalborg, Denmark, *published* (Li et al. (2013a))

Paper 5, **the potential cost from passengers and how it impacts railway maintenance and renewal decisions** presents the importance of considering passenger loss into cost estimation for railway track possession decision. A phase-based planning toolkit is introduced to compare project proposals from a wider range of cost, integrating passenger loss into cost comparison.

The case study shows that the passenger loss due to delay could dominate the overall cost comparison for the railway stations with tight train time tables. In such case, the track possession should be chosen to avoid passenger delay instead of only focusing on direct costs. The work has been disseminated as follows:

- Rui Li, Alex Landex, Steen Nørbæk Madsen, Otto Anker Nielsen, "The potential cost from passengers and how it impacts railway maintenance and renewal decisions", *Trafikdage*, 2013, Aalborg, Denmark, *presented* (Li et al. (2013b))

Chapter 6

MAIN CONCLUSIONS AND FUTURE RESEARCH

Railway maintenance is critical to ensure railway safety, train punctuality and a good overall utilization of capacity. An increasing demand for railway services has conflicts with the existing limited railway network and railway maintenance budget. Mathematical optimization is needed to improve the current practices for railway maintenance scheduling and railway projects planning.

This study is carried out to develop a Phase-Based Decision Support System (PDSS) to help railway infrastructure managers to plan railway maintenance and infrastructure projects more economically, i.e. cost-effective. The thesis introduces two types of PDSS, i.e. Functional Phase-Based Planning Approach (F-PBPA) and Process-Oriented Phase-Based Planning Approach (PO-PBPA). In the F-PBPA, New Mixed Integer Linear Programming models were formulated for Railway Preventive Condition-Based Tamping Scheduling Problem (RPCBTSP), and for Railway Track Possession Scheduling Problem (RTPSP). While the PO-PBPA provides decision support in terms of the ability to introduce and thus calculate project cost from the Life Cycle Cost (LCC) perspective. The outputs can be used to respectively compare and identify the most cost efficient planning solution.

The work in this thesis contributes to the OR literature and non-OR literature, and has been disseminated in peer-reviewed journals and conferences. The contributions cover phase-based methodology, OR modelling, and computational results. There are five research papers included in the thesis and they concern railway infrastructure project planning and provide decision support at the strategic planning level. The real data are collected from two Danish railway corridors and tested in the case studies.

For the RPCBTSP, We improved the existing OR model in the literature by considering a number of practical issues such as preparation cost and driving cost, the time value for costs and a more realistic estimation of the tamping recovery. As a result of testing on the Danish railway corridor between Odense and Frederica, the computational results show that it is important to consider extra cost components. The schedule obtained by only concerning the technical factors is in fact 59% more expensive than the schedule by integrating the economic factors.

This thesis presents a concept of the phase-based planning. The proposed PDSS (F-PBPA) represents progress in solving scheduling problems for railways, and it can help Infrastructure Managers (IMs) to gain a better understanding of mathematical optimization models. There are three optimization phases, i.e., Technical Optimization (TeO), Economic Optimization (EcO), and Constrained Optimization (CoO). By implementing them in order, there can firstly identify minimal number of maintenance assessed only by technical conditions in TeO. This is followed by an EcO, which results in an economic plan covering the same technically defined maintenance needs while minimizing the costs. Then, CoO includes additional constraints and it allows the railway expert to adjust input parameters, thereby obtaining alternative maintenance plans. The proposed PDSS (F-PBPA) can therefore provide decision support.

The thesis introduces a new schedule problem, RTPSP, which considers a large-scale railway infrastructure project to determine when to perform which construction works and in which track possessions, while satisfying different operational constraints and minimizing the total construction cost. The RTPSP is new problem which has not been defined in literature. The proposed mathematical models are based on the current Excel-based calculation from Rambøll Denmark. To find an optimal solution of the RTPSP, the thesis proposes an approach that, first, transfers the nominal market prices into track-possession-based real prices, and then generates a schedule of the construction works by solving a proposed MILP model for the given track blocking proposal. The proposed approach is tested on a real-life case study from the Danish railway infrastructure manager. The results show that, in 2 hours of computing time, the approach is able to provide solutions that are within 0.37% of the optimal one, so it can be used as an effective support tool, at the primary planning stage, to suggest preferable track possessions within the existing railway services.

The PO-PBPA recommended by the thesis, contains a systematic process, from the LCC perspective, to estimate project overall cost step by step. A new LCC framework is suggested for the cost estimation. A case study shows that the railway project decision, compared to the current practices, might change if considering passenger loss into account. Identifying the less expensive solution in terms of LCC could help railway infrastructure managers, from a wider scope of cost, to reduce long term investments.

The proposed PDSS concept in the thesis is a new step solving railway maintenance scheduling problem and railway infrastructure projects planning problem. Besides providing the optimization models, the thesis also provides a phase-base planning system. Through the logical orders in the PDSS's, it can help to reduce railway costs without impacting track quality.

This work can be extended in several directions in the future. Firstly, the same phase-based concept of planning in TeO, EcO and CoO phases, can be applied to the other railway systems such as railway catenary system and railway switches, where both the technical status and the economic factors need to be considered for maintenance decisions. Secondly, the F-PBPA method can also be applied for railway track renewals scheduling problems. Lastly, a heuristic or meta-heuristic algorithm, adding geometry location, could be included if the planning scope need to be extended from a corridor to railway network.

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Paper 1

Optimization of preventive condition-based tamping for railway tracks

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Optimization of preventive condition-based tamping for railway tracks

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ABSTRACT

This work considers the scheduling of railway preventive condition-based tamping, which is the maintenance operation performed to restore the track irregularities to ensure both safety and comfort for passengers and freight. The problem is to determine when to perform the tamping on which section for given railway tracks over a planning horizon. The objective is to minimize the Net Present Costs (NPC) considering the following technical and economic factors: 1) track quality (the standard deviation of the longitudinal level) degradation over time; 2) track quality thresholds based on train speed limits; 3) the impact of previous tamping operations on the track quality recovery; 4) track geometrical alignment; 5) tamping machine operation factors and finally 6) the discount rate.

In this work, a Mixed Integer Linear Programming (MILP) model is formulated and tested on data from the railway corridor between Odense and Fredericia, part of the busiest main line in Denmark. Computational experiments are carried out to compare our model to the existing models in the literature. The results show that taking into consideration these previously overlooked technical and economic factors 3, 5 and 6 can prevent under-estimation of required tamping operations, produce a more economic solution, prevent unnecessary early tamping, and improve the track quality by 2 percent.

1. Introduction

For modern railways, maintenance is critical to ensure safety, punctuality and a good overall utilization of capacity. The maintenance cost in Europe ranges from 30,000 to 100,000 Euro per kilometer railway track per year (Jimenez-Redondo et al., 2012). Appropriate planning of the railway maintenance is highly desired in order to maintain the necessary condition of the infrastructure that economic and social activities heavily rely on. However, such a task is very complex and particularly difficult to make and execute (Chu & Chen, 2012) due to the fact that a large number of factors, such as geographical factors, topographical factors, track alignment, climatic conditions, rolling stocks, maintenance budgets, track availability etc., need to be considered (Zoeteman, 2001).

One of the most important, while expensive, track maintenance operations is tamping, i.e. repair of track irregularities by correcting the standard deviation of the longitudinal level, the geometrical parameter that affects the rolling stocks and track dynamics the most, to such a level that the error in the longitudinal level does not exceed a certain threshold for safety and comfort for passengers and freight (Vale, Ribeiro, & Calcada, 2012). According to Rail Net Denmark, the infrastructure manager in Denmark, over 110 million Danish kroner (DKK) are spent on tamping-related maintenance every year (Rail Net Denmark, 2013a). Previous studies have shown that optimizing tamping activities can lead to substantial savings in maintenance costs (Grimes & Barkan, 2006; Kong & Frangopol, 2003; Macke & Higuchi, 2007; Uzarski & Mcneil, 1994; Vale & Lurdes, 2013).

It is therefore important to split the tamping procedure into corrective tamping for isolated defects and preventive tamping for Stations, Swithes and Crossings (S&C's), and open lines, respectively, as these two types of tamping operations are planned in different ways. This paper will only focus on maintenance tamping for open lines with a view to finding the optimal tamping schedule for given railway tracks over a given planning horizon consisting of a number of periods. The railway tracks are divided into a number of sections of the same length. The track quality of each section is measured by its standard deviation of the longitudinal level and is furthermore expected to degrade over time and hence to be improved/maintained by a tamping operation. The quality improvement resulting from a tamping operation is determined by both the current quality when the tamping operation is performed and by previously performed tamping operations. The goal is to decide when to perform tamping operations on which railway sections so

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that the Net Present Costs (NPC), the sum of the present value of all costs, is minimized over the planning horizon. The costs include the tamping cost, the preparation cost before and after tamping, and the cost of driving the tamping machine through the track. The main goal of this paper is to propose a mathematical model to solve this problem and to apply the model on Danish railways.

In the literature, mathematical programming has been applied to obtain the optimal solution to the Preventive Maintenance Scheduling Problem (PMSP). One of the earliest studies was provided by Wagner, Giglio, and Glaser (1964). They considered a general problem of scheduling a number of given projects, each of which had a fixed duration and should be started in one of the possible starting periods, and proposed five MILP models for different optimization criteria. Higgins, Kozan, and Ferreira (1996) studied the problem of track maintenance activity scheduling and presented a model to minimize a weighted combination of expected interference delays and prioritized finishing time of activities. The computational result on an 89 kilometer track corridor in Australia showed that the model can provide a better solution, more than 7 percent in terms of objective value, than manual planning. Budai and Dekker (2004) considered the optimization of railway maintenance schedules for both routine maintenance works and one-time maintenance projects. They developed models to minimize the possession time, possession cost and maintenance cost. Oyama and Miwa (2006) presented models to maximize the total expected improvement obtained by a given number of tamping operations within a 1-year planning horizon. Another major type of maintenance problems is to find the maintenance thresholds that optimize the infrastructure conditions under budget constraints. Chu and Chen (2012) proposed a hybrid dynamic model which combines both continuous and discrete states to find the optimal thresholds for multiple maintenance actions with different effects. Khurshid et al. (2011) addressed the problem by using concepts of cost-effectiveness analysis.

The work most relevant to ours is provided by Vale et al. (2012) and Vale and Ribeiro (2014), both of which attempted to find the optimal schedule for preventive tamping maintenance. Compared to our problem, their problem has a different objective, i.e., minimizing the total number of tamped sections over a given planning horizon. In Vale et al. (2012), the deterioration rate for a given railway section, i.e., the increase of the standard deviation of the longitudinal level over one period, is assumed to be constant, whereas, in Vale and Ribeiro (2014), it varies in different periods and is simulated by Monte Carlo techniques. The rest of the problem settings are exactly the same in both works. They formulated the problem as MILP model, solved it by CPLEX and presented the results on a Portuguese Northern Railway Line.

The main contribution of this work is in extending the problem in Vale et al. (2012) by including a number of additional important practical factors. More specifically: 1) we consider a more realistic cost and minimize the overall cost, whereas (Vale et al., 2012) only minimizes the number of tamping operations; 2) we minimize the NPC, and as a result avoid unnecessary early tamping and improve the track quality at the end of the planning horizon; 3) compared with Vale et al. (2012) which only considers the linear dependency between the quality recovery and the current track quality, we estimate the tamping recovery based on both the current track quality and the impact of previous tamping operations, which has been proven relevant (Caetano & Teixeira, 2014; Chang, Liu, & Li, 2010; Esveld, 2001; Ferreira & Murray, 1997; Quiroga & Schnieder, 2012; UIC, 2008; Veit, 2006; Zoeteman, 2001, 2006) and leads to a more realistic estimation. We have formulated the problem as a Mixed Integer Linear Programming (MILP) model and carried out intensive computational experiments on the data from one of the busiest railway corridors in Denmark, the corridor linking Odense and Fredericia (Od–Fa).

The remainder of this paper consists of a detailed description of the problem (Section 2), the MILP model (Section 3), the computational results (Section 4) and a conclusion (Section 5).

2. Problem description

The problem of consideration is an optimization of preventive condition-based tamping maintenance for a given railway track over a planning horizon consisting of a number of periods. The railway tracks are discretized into a number of consecutive sections of the same length. In tamping practice, the tamping machine travels on top of the railway track from one end (the first section) to the other (the last section) and applies tamping operation on the sections if necessary, when it passes through the sections. The track quality (TQ) of each section is measured by its standard deviation of the longitudinal level and is furthermore expected to degrade over time and hence improved/maintained by a tamping operation. The degradation is assumed to be a linear function of time, which is the same as in Vale et al. (2012), and not allowed to exceed a certain threshold limit. The initial quality, degradation rate and threshold value of each section are assumed to be known. Finally, there is the tamping recovery, i.e. the improvement in quality depending on a set of different factors. Firstly, there is a linear relationship between the quality recovery and the quality before tamping. The International Union of Railways (UIC[1]) denotes that if the current standard deviation of the longitudinal level before tamping is σ, the tamping recovery can be no more than

$$\theta(\sigma) = a \cdot \sigma + b \tag{1}$$

where a and b are given parameters and $\theta(\sigma)$ is the quality-dependent recovery upper bound. Secondly, the recovery is also dependent on the previous tamping operations because tamping itself may crash the ballast, which is the main factor of track stability as shown in many previous studies (Caetano & Teixeira, 2014; Chang et al., 2010; Esveld, 2001; Ferreira & Murray, 1997; Quiroga & Schnieder, 2012; UIC, 2008; Veit, 2006; Zoeteman, 2001, 2006). Therefore, the resultant quality of the present tamping can never be better than the resultant quality of the previous tamping. We name the maximum recovery bounded by the previous tamping as previous-tamping-dependent recovery upper bound. The tamping recovery is set to the smaller value of the two above-mentioned upper bounds.

To illustrate how the quality recovery is calculated, an example is given in Table 1. In this example, we assume that the initial TQ (σ_0) is 0.4, the degradation rate is 0.2 for each period, the linear dependency parameters a and b in Eq. (1) are 0.6 and -0.2, respectively, and a tamping operation is performed in the periods 3 and 4. At the end of period 3, the TQ can be recovered by a standard deviation ($\theta_3^Q = 0.4$) according to quality-dependent-recovery in Eq. (1). The resultant standard deviation after tamping (σ_3) equals 0.6, which then becomes a lower bound for the future tamping operations, i.e., $\underline{\sigma_i} = 0.6$ for $i \geq 4$. In period 4, although the quality dependent recovery (θ_4^Q) may reduce the standard deviation by 0.28 according to Eq. (1), the actual recovery can only yield an improvement of standard deviation by 0.2 due to the bound given by the previous tamping in period 3.

Fig. 1 illustrates how the track quality changes from periods 0 to 6. The x-axis and y-axis correspond to the time period and the standard deviation of the longitudinal level (σ_i), respectively. The curves depict the track quality with and without the previous-tamping-dependent recovery upper bound (θ_i^T). It can be seen that taking into consideration the upper bound θ_i^T can prevent over-estimation of the tamping recovery and can consequently prevent under-estimation of the total tamping cost.

[1] UIC: *Union Internationale des Chemins de fer* in French.

Table 1
Quality recovery illustration.

Period (i)	TQ (σ_i)	Tamping? (Y/N)	Minimum TQ which can be achieved ($\underline{\sigma_i}$)	TQ recovery upper bounds: Quality-dependent ($\theta_i^Q = 0.6 \cdot \sigma_i - 0.2$)	Previous-tamping-dependent ($\theta_i^T = \sigma_i - \underline{\sigma_i}$)	Tamping: Tamping recovery ($\theta_i = min\{\theta_i^Q, \theta_i^T\}$)	TQ after tamping ($\sigma_i' = \sigma_i - \theta_i$)
0	0.4	N	0.4				0.4[a]
1	0.6	N	0.4				
2	0.8	N	0.4				
3	1.0	Y	0.4	0.40	0.6 (= 1.0–0.4)	0.4	0.6
4	0.8	Y	0.6	0.28	0.2 (= 0.8–0.6)	0.2	0.6
5	0.8	N	0.6				
6	1.0	N	0.6				

[a] Initial TQ is treated as TQ after tamping (σ_i').

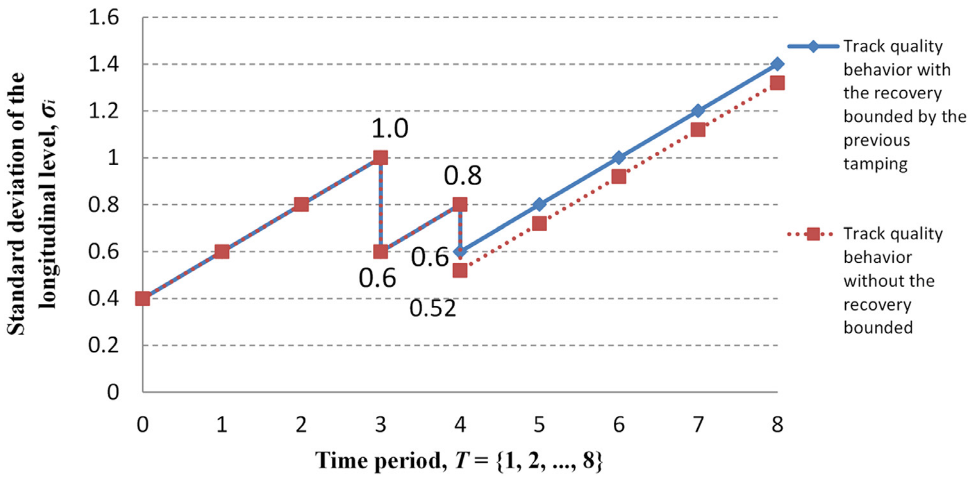

Fig. 1. Track behavior comparison.

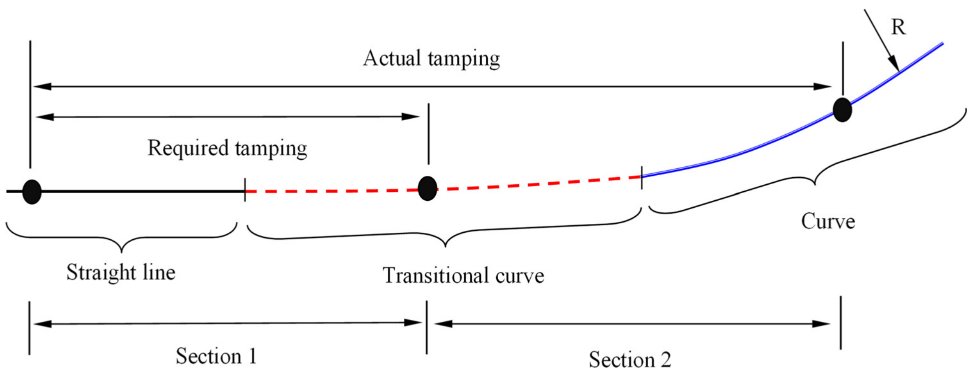

Fig. 2. Track layout influences on tamping schedule.

Furthermore, trace alignment, known as track horizontal layout, can influence the tamping schedule. It is caused by a transition curve which is a mathematically calculated curve with gradually raised radii on railway tracks. Due to the way a tamping machine is operating, it is forbidden to start/stop in a transition curve according to operation rules mentioned in Rail Net Denmark (2013b); UIC (2008) and Vale et al. (2012). If a track section to be tamped ends inside a transition curve, the tamping operations should be extended to the next section(s), which end(s) outside a transition curve. An example is illustrated in Fig. 2, in which Section 1 starts with a straight line and ends inside a transition curve and Section 2 starts from a transition curve and ends inside a curve with constant radius. If Section 1 requires a tamping operation, the tamping operation should be extended to Section 2, and vice versa. As a result, these two sections should always be tamped together. We refer to such sections as transition alignment.

During the planning of tamping operations we make decisions on when to tamp which section with the objective of minimizing the NPC over the planning horizon. The total cost consists of three components: a fixed cost of driving the tamping machine through the entire railway track if any section is tamped in that period; a unit tamping cost for each section; a unit cost of machine preparation for each tamping operated on a single section or consecutive sections to account for the warming up and ramping down of tamping machines. The fixed cost, the unit tamping cost and the unit preparation cost as well as the period discount rate are given.

3. Mathematical formulation

Let $N = \{1, \ldots, n\}$ denote the set of railway track sections and $T = \{1, \ldots, m\}$ the set of time periods. For each section $i \in N$, let $I(i) \subseteq N$ denote the transition alignment that i belongs to. If neither of the two ending points of section i lies in a transition curve,

$I(i) = \{i\}$. Let parameter l_i, d_i and e_i denote the initial longitudinal deviation, the degradation rate, and the threshold value for section i. The fixed cost, unit tamping cost and unit preparation cost are denoted by parameter f, c and k. The discount rate is denoted as parameter rT. Let parameter o_i be the initial value for minimal longitudinal deviation that can be achieved by tamping i at period 0. Let M be a sufficiently large number used in the big-M constraints. Without loss of generality, we assume tamping takes place at the end of each period.

Let binary variable x_i^t equal 1 if section $i \in N$ is tamped in time period $t \in T$ and 0 otherwise, binary variable z^t equal 1 if any tamping takes place in period $t \in T$ and 0 otherwise, and binary variable y_i^t equal 1 if the tamping machine needs to be prepared when tamping section $i \in N$ in period $t \in T$ and 0 otherwise.

Let variable σ_i^t be the standard deviation of the longitudinal level of section $i \in N$ at the end of period $t \in T$. It should be noted that, if section i is tamped in period t, σ_i^t refers to the longitudinal deviation after tamping. Let variable σ_i^0 be the standard deviation of the longitudinal level at period 0 and is initialized by parameter l_i. Let variable w_i^t be the tamping quality recovery of section $i \in N$ in period $t \in T$, which should take the smaller value of the quality-dependent recovery upper bound (denoted by variable r_i^t) and the preceding-tamping-dependent recovery upper bound (denoted by variable s_i^t). To formulate this relation by linear constraints, we introduce an auxiliary binary variable v_i^t ($i \in N$, $t \in T$), which equals 1 if $s_i^t > r_i^t$ and 0 if $s_i^t < r_i^t$.

The value of r_i^t ($i \in N$, $t \in T$) depends on the linear dependency function (1) and equals $\max\{0, a(\sigma_i^{t-1} + d_i) + b\}$ since it makes no sense to have a negative value for the recovery. To formulate it as linear constraints, we introduce an auxiliary binary variable q_i^t, which equals 1 if $a(\sigma_i^{t-1} + d_i) + b > 0$ and 0 if $a(\sigma_i^{t-1} + d_i) + b < 0$.

Let variable u_i^t be the minimal longitudinal deviation that can be achieved by tamping $i \in N$ in period $t \in T$, which equals to the resultant deviation of the previous tamping. Let variable u_i^0 be initial value for minimal longitudinal deviation for period 0, which is initialized by parameter o_i.

The mixed integer linear programming formulation of the preventive condition-based tamping scheduling problem is presented as follows.

Minimal Cost Model (MCM):

$$\min \sum_{t\in T} [\left(\sum_{i\in N} c \cdot x_i^t + \sum_{i\in N} k \cdot y_i^t + f \cdot z^t\right) \cdot \left(\frac{1}{1+rT}\right)^t \quad (2)$$

subject to

$$y_1^t \ge x_1^t \quad \forall t \in T \quad (3)$$

$$y_i^t \ge x_i^t - x_{i-1}^t \quad \forall i \in N, \quad t \in T, i \ge 2 \quad (4)$$

$$x_i^t \le z^t \quad \forall i \in N, \quad t \in T \quad (5)$$

$$x_l^t \ge x_i^t \quad \forall i \in N, \quad l \in I(i), t \in T \quad (6)$$

$$\sigma_i^0 = l_i \quad \forall i \in N \quad (7)$$

$$\sigma_i^{t-1} + d_i \le e_i \quad \forall i \in N, \quad t \in T \quad (8)$$

$$\sigma_i^t = \sigma_i^{t-1} + d_i - w_i^t \quad \forall i \in N, \quad t \in T \quad (9)$$

$$w_i^t \le M \cdot x_i^t \quad \forall i \in N, \quad t \in T \quad (10)$$

$$s_i^t - M \cdot \left(1 - x_i^t\right) - M \cdot v_i^t \le w_i^t \le s_i^t \quad \forall i \in N, \quad t \in T \quad (11)$$

$$r_i^t - M \cdot \left(1 - x_i^t\right) - M \cdot (1 - v_i^t) \le w_i^t \le r_i^t \quad \forall i \in N, \quad t \in T \quad (12)$$

$$M \cdot (v_i^t - 1) \le s_i^t - r_i^t \le M \cdot v_i^t \quad \forall i \in N, \quad t \in T \quad (13)$$

$$M \cdot \left(q_i^t - 1\right) \le a\left(\sigma_i^{t-1} + d_i\right) + b \le M \cdot q_i^t \quad \forall i \in N, \quad t \in T \quad (14)$$

$$r_i^t \le M \cdot q_i^t \quad \forall i \in N, \quad t \in T \quad (15)$$

$$r_i^t \ge a\left(\sigma_i^{t-1} + d_i\right) + b - M \cdot \left(1 - q_i^t\right) \quad \forall i \in N, \quad t \in T \quad (16)$$

$$r_i^t \le a\left(\sigma_i^{t-1} + d_i\right) + b + M \cdot \left(1 - q_i^t\right) \quad \forall i \in N, \quad t \in T \quad (17)$$

$$s_i^t = \sigma_i^{t-1} + d_i - u_i^t \quad \forall i \in N, \quad t \in T \quad (18)$$

$$u_i^0 = o_i \quad \forall i \in N \quad (19)$$

$$u_i^{t-1} - M \cdot x_i^{t-1} \le u_i^t \le u_i^{t-1} + M \cdot x_i^{t-1} \quad \forall i \in N, \quad t \in T \quad (20)$$

$$u_i^t \ge \sigma_i^{t-1} - M \cdot \left(1 - x_i^{t-1}\right) \quad \forall i \in N, \quad t \in T \quad (21)$$

$$u_i^t \le \sigma_i^{t-1} + M \cdot \left(1 - x_i^{t-1}\right) \quad \forall i \in N, \quad t \in T \quad (22)$$

$$x_i^t, y_i^t, z^t, q_i^t, v_i^t \in \{0, 1\} \quad \forall i \in N, \quad t \in T \quad (23)$$

$$\sigma_i^t, w_i^t, r_i^t, u_i^t, s_i^t \ge 0 \quad \forall i \in N, \quad t \in T \quad (24)$$

$$z^t \in \{0, 1\} \quad \forall i \in N \quad (25)$$

The objective function (2) minimizes the NPC over the entire planning horizon. Constraints (3) and (4) define the relationship between the y-variables and the x-variables. There are two cases where the tamping machine should be prepared, 1) if the first section requires tamping, the machine should be warmed up at Section 1 by constraint (3), and 2) if section $i-1$ does not require tamping but section i does, the machine should be warmed up at section i by constraint (4). Constraints (5) set z^t to 1 if tamping takes place at any section in period z^t. Constraints (6) make sure that tamping begins and ends outside transition curves. If $x_i^t = 1$, then $\sum_{l\in I(i)} x_l^t \ge |I(i)|$ will force all the sections in $I(i)$ to be tamped.

Constraints (7–9) keep track of the track quality at each section in each period. Constraints (7) initialize the longitudinal deviations and Constraints (8) enforce the bound values. Constraints (9) set the quality of section i at the end of period $t \ge 1$ (σ_i^t) based on the quality at the end of the previous period (σ_i^{t-1}), the degradation within one period (d_i), and the tamping quality recovery (w_i^t).

Constraints (10–13) determine the value of the quality recovery (w_i^t). If section i is not tamped in period t, i.e. $x_i^t = 0$, w_i^t is set to 0 by Constraints (10). Otherwise, w_i^t is set to the smaller value of r_i^t and s_i^t by Constraints (11) and (12). If $s_i^t < r_i^t$, then v_i^t is set to 0 by Constraints (13) and w_i^t to s_i^t by Constraints (11). If $s_i^t > r_i^t$, then v_i^t is set to 1 by Constraints (13) and w_i^t to r_i^t by Constraints (12).

Constraints (14–17) determine the value of the quality-dependent recovery upper bound (r_i^t). If $a(\sigma_i^{t-1} + d_i) + b > 0$, then q_i^t is set to 1 by Constraints (14) and r_i^t to $a(\sigma_i^{t-1} + d_i) + b$ by Constraints (16) and (17). If $a(s_i^{t-1} + d_i) + b < 0$, then q_i^t is set to 0 by Constraints (14) and r_i^t to 0 by Constraints (15).

Constraints (18) set the value of the preceding-tamping-dependent recovery upper bound (s_i^t) to the difference between the quality before tamping ($\sigma_i^{t-1} + d_i$) and the minimal longitudinal deviation (u_i^t) that can be achieved . Constraints (19) initialize the value of u_i^t for section i in period t. Constraints (20–22) determine the value of u_i^t based on u_i^{t-1} and x_i^{t-1}. If $x_i^{t-1} = 0$, u_i^t is set to u_i^{t-1} by Constraints (20). Otherwise, it is set to σ_i^{t-1}, the resultant longitudinal deviation of the tamping in period $t-1$.

Finally, all variables are defined by Constraints (23–25).

Comparison between our model and the existing model in the literature

The model in Vale et al. (2012) only minimizes the total number of tamping operations and does not consider the impact of previous tamping on the quality recovery. It is equivalent to:

Minimal Tamping Model (MTM):

$$\min \sum_{t\in T}\sum_{i\in I} x_i^t \tag{26}$$

subject to
constraints (6–10,12,14–17,23–24).

Our MCM model extends MTM in a few ways. Firstly, our model considers the impact of the previous tamping on the quality recovery as reflected by constraints (11,13,18–22). We call these constraints New Recovery Constraints (NRC). The absence of NRC may lead to over-estimation of the quality recovery. In an extreme case, the quality could be improved by tamping continuously until the longitudinal level deviation is reduced to zero. This can never be true in reality. Therefore, these constraints should therefore be included in the model.

The second extension is to minimize the total cost instead of the total number of tamping operations as formulated by constraints (3–5). These constraints more closely represent the real-life overall cost because the number of tamping operations only relates to tamping cost, which corresponds to one of the cost components. The cost of tamping one section in every period over a ten-period planning horizon is different from the cost of tamping ten consecutive sections in one period.

The last extension is the inclusion of NPC in the objective function (2), indicating, for example, that a tamping at later time period becomes cheaper than the current. This is a practical consideration and helps to avoid unnecessary early tamping and improve the quality at the end of the planning horizon.

The importance of these extensions and their impact on the maintenance schedule will be shown through computational experiments in Section 4.

4. Case study: Computational experiments

The proposed model is tested on the real-life data provided by Rail Net Denmark (Banedanmark in Danish), the national railway infrastructure manager in Denmark. MILP models are solved by CPLEX version 12.6.0.0. Section 4.1 describes the case study and the included data, and Section 4.2 presents the computational results on different models and the sensitivity analysis.

4.1. Case study

The case study revolves around a Danish railway corridor linking Odense and Fredericia (Od–Fa) with a length of 57.2 kilometer (including 14.6 kilometer of stations and 42.6 kilometer of open tracks) as shown in Fig. 3. It is one part of the busiest main line linking the four biggest cities, Copenhagen, Odense, Aarhus and Aalborg in Denmark. It is comprised of both national (Copenhagen–Aalborg) travelers and international (Nordic countries–Central Europe) passengers and freight. The track system consists of one type of rails (UIC60[2], five types of sleepers and two sub-layer structures. It is a simple double-track structure and is well documented both on infrastructure layout, traffic, geometric quality surveys, and maintenance records. Only the right track is included in the experiment. The corridor is divided into 220 consecutive track sections in total, each with a length of 200 meters. The planning horizon consists of fourteen 90-day periods.

[2] UIC60: It is a standard rail profile defined in European Standard EN-13674.

In Denmark, the longitudinal geometry of the railway track is measured by a monitoring vehicle four times every year on the main lines for safety reasons. The measurement data collected from 2007/03/19 to 2012/11/26 are used to generate the test instances for this study. The linear degradation of each section is obtained using the linear regression. Ten instances were generated in total, all of which have the same quality threshold parameters, transition alignments parameters and track degradation parameters. The only difference lies in the initial quality parameters. The initial quality of each instance is taken from a random historical measurement.

The track quality of each section on November 26, 2012 as well as the threshold values defined in Rail Standard BN1-38-4 (2011) are depicted in Fig. 4. The variations in the track quality threshold values of different sections are from the result of different speed classes of rolling stock. In practice, a track quality slightly higher than the preventive threshold does not endanger the passenger safety, but indicates that a tamping has to be scheduled for the next period (Rail Net Denmark, 2013b). Thus, MCM treats these threshold values as hard constraints which ultimately are therefore not allowed to be exceeded. It can be seen from the figure that the track quality is good due to the prioritized maintenance/renewals in the past.

The track alignments example are denoted in Fig. 5, which only includes the track sections between Odense station and Holmstrup station, approximately a 6 kilometer stretch. The horizontal alignment is shown by the solid line indicating the straight stretches, the transition curves and the curves. The separate dots denote the section edges. The dashed frames highlight the sections linked by transition curves, indicating that 'bundling' tamping should be implemented. The track degradation of each section is derived from the data collected in the period from August 2008 to November 2012. The parameters a and b from (1) are set to 0.63 and -0.23, according to the Office for Research and Experiments (ORE) 1988 of UIC (Esveld, 2001) and the Danish tamping improvement project (de Saint-Aubain, Kulahci, Ersbll, & Spliid, 2012).

Tamping costs are also provided by Rail Net Denmark. They are measured by time (in minutes): It takes 12 minutes to tamp a section, 20 minutes to warm up and ramp down the machine, and approximately half a minute (25 kilometer/hour) to drive through a section without tamping.

4.2. Results

To investigate the impact of the different extensions introduced in MCM, different models were tested and the produced results compared. The tested model runs include: 1) MTM, 2) MTM with NRC constraints (MTM+NRC), 3) MCM without interest rate (MCM-INT), i.e., $rT = 0$ in MCM, 4) MCM without NRC (MCM-NRC), and 5) the MCM.

For each model run, the number of tamping operations (#Tamp), the number of machine preparations (#prep), the total tamping cost (C_t), the total fixed cost (C_d), the total machine preparation cost (C_p), and the total cost (C_{tot}) are presented in Table 2. For MCM and MCM-NRC, the NPC is also presented. As different models have different objective functions, the objective values are indicated by 'OBJ' in the table. The average value of each column is given in the bottom row.

4.2.1. The necessity of the NRC

The effect of NRC on the MTM model is analyzed by comparing the results of two model runs, namely the base case MTM and MTM+NRC. Fig. 6 depicts the total number of tamping operations given by the two models for all data instances. As can be seen, without the realistic correction in the quality recovery in the NRC,

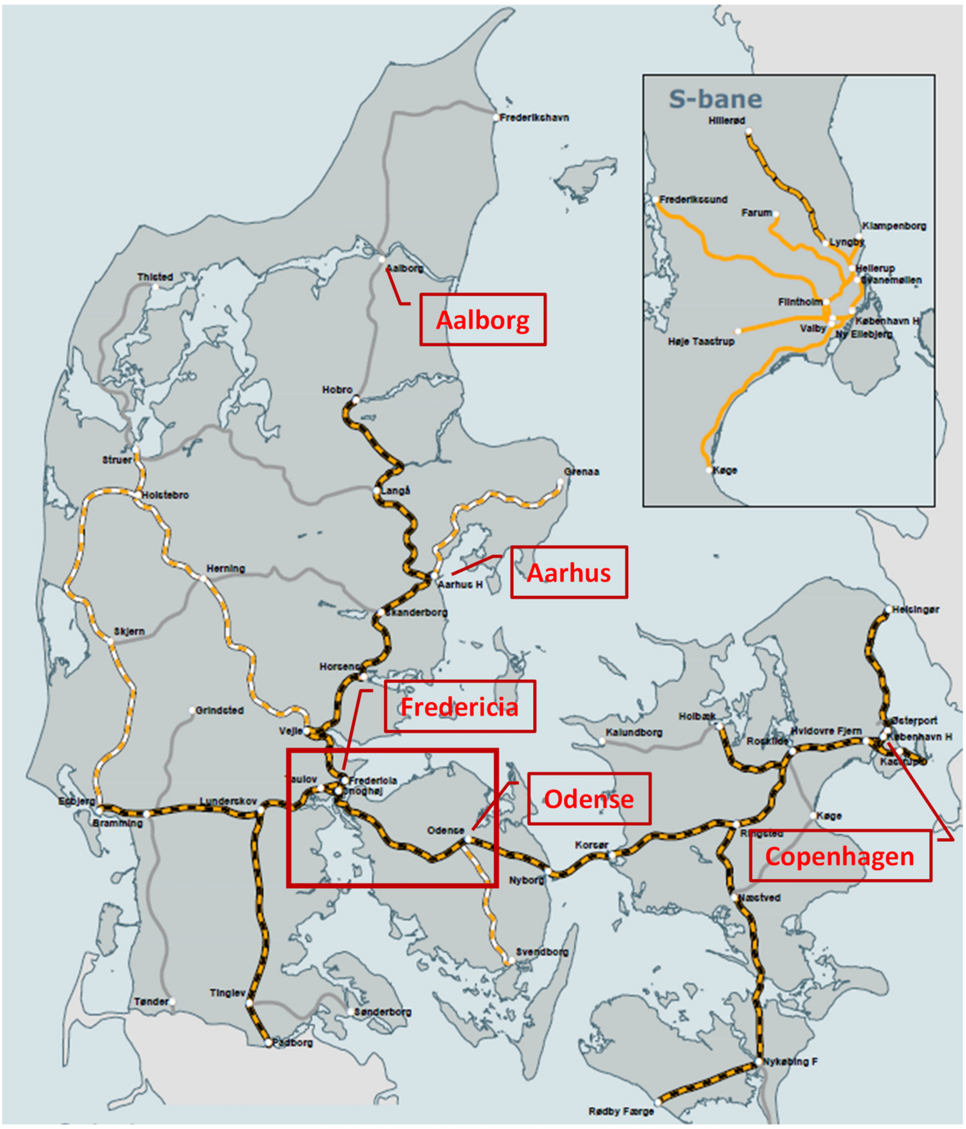

Fig. 3. The Od–Fa corridor in the Danish railway network of Rail Net Denmark (2014).

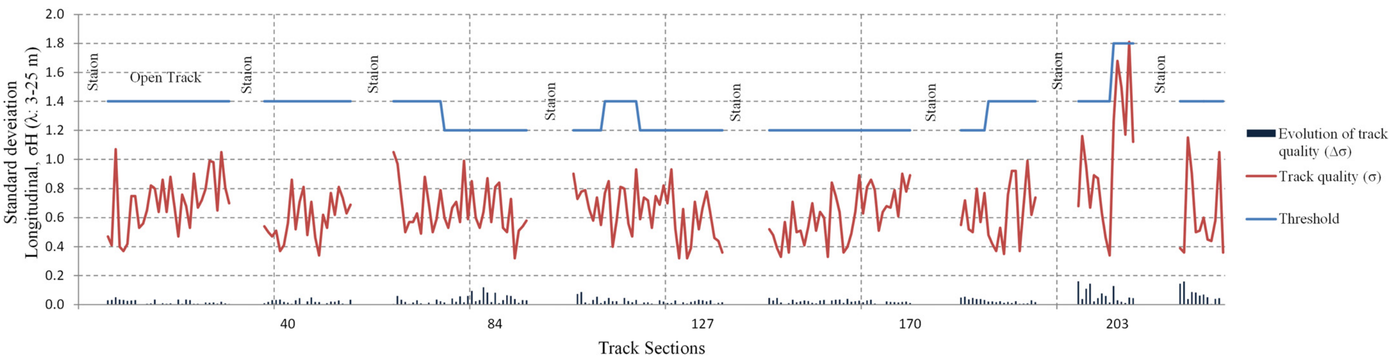

Fig. 4. The initial track quality, the track degradation and the thresholds in the Od–Fa Corridor.

the total number of tamping operations may be under-estimated by up to 3. To illustrate this further, Fig. 7 presents a fixed example depicted through section 196 in data Instance 10. The longitudinal level deviation of the section at the end of each period (σ^t_{196}) given by both models are shown. Without the NRC, the quality recovery is over estimated, which leads to an under-estimated number of required tamping operations. Similar effects on the MCM model can be observed by comparing the results of MCM-NRC and MCM. Without NRC, the objective value, i.e. the total maintenance cost NPC, is under-estimated by up to 10 percent and on average 4 percent (Fig. 8).

4.2.2. Minimization of total cost vs. # tamping operations

The comparison between the objective of minimizing the total maintenance cost and the objective of minimizing the total

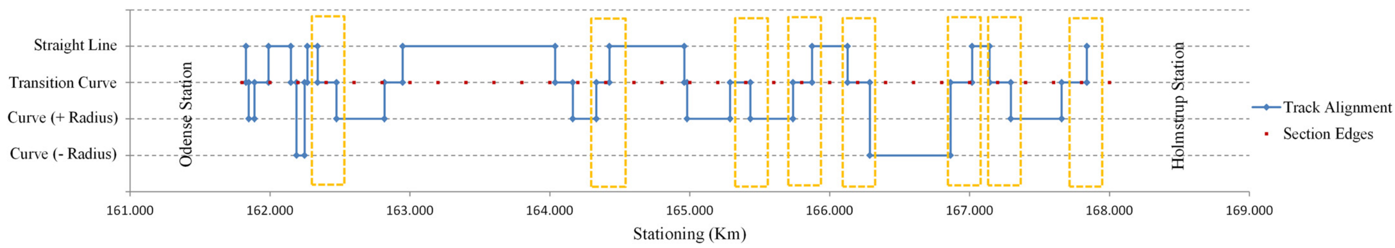

Fig. 5. The track alignment layout example (Odense–Tommerup).

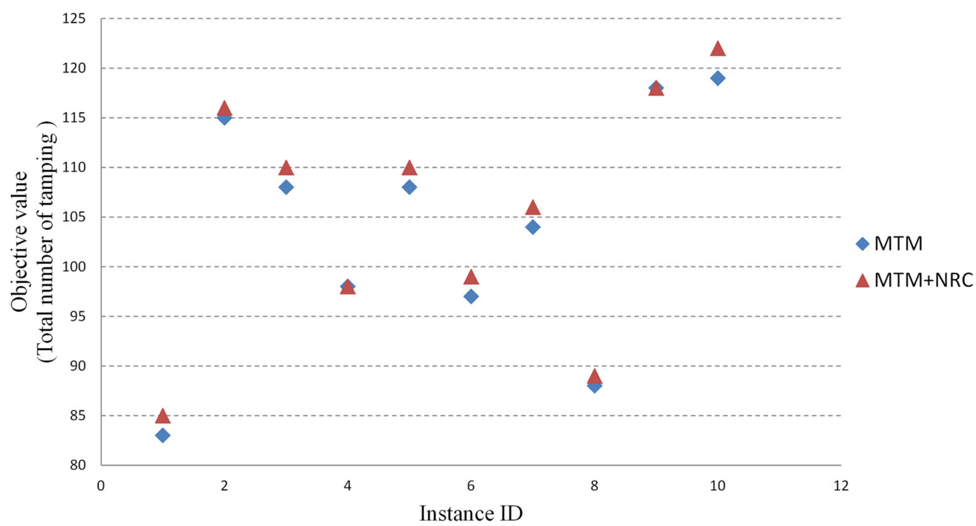

Fig. 6. The impact of NRC on the MTM model.

Table 2
The results from different models.

Instances	MCM-NRC								MCM-INT						
	#Tamp	#prep	C_p	C_d	C_t	C_{tot}	NPC (OBJ)	s_{End}	#Tamp	#prep	C_p	C_d	C_t	C_{tot} (OBJ)	s_{End}
1	94	35	700	504	1128	2332	2148	0.87	95	35	700	504	1140	2344	0.89
2	137	47	940	483	1644	3067	2849	0.87	138	48	960	483	1656	3099	0.89
3	123	44	880	490	1476	2846	2658	0.91	132	49	980	623	1584	3187	0.92
4	117	49	980	493	1404	2877	2688	0.89	118	50	1000	492	1416	2908	0.91
5	124	44	880	490	1488	2858	2667	0.87	129	48	960	624	1548	3132	0.89
6	116	42	840	493	1392	2725	2537	0.89	124	44	880	627	1488	2995	0.90
7	121	45	900	491	1452	2843	2641	0.89	121	45	900	628	1452	2980	0.92
8	102	38	760	500	1224	2484	2307	0.89	104	38	760	499	1248	2507	0.91
9	135	47	940	484	1620	3044	2842	0.88	136	47	940	484	1632	3056	0.91
10	139	50	1000	482	1668	3150	2961	0.89	135	57	1140	622	1620	3382	0.91
Average	**121**	**44**	**882**	**491**	**1450**	**2823**	**2630**	**0.88**	**123**	**46**	**922**	**559**	**1478**	**2959**	**0.91**

Inst.	MTM						MTM+NRC						MCM							
	#Tamp (OBJ)	#prep	C_p	C_d	C_t	C_{tot}	#Tamp (OBJ)	#prep	C_p	C_d	C_t	C_{tot}	#Tamp	#prep	C_p	C_d	C_t	C_{tot}	NPC (OBJ)	s_{End}
1	83	57	1140	1745	996	3881	85	66	1320	1881	1020	4221	95	35	700	504	1140	2344	2157	0.87
2	115	87	1740	1729	1380	4849	116	84	1680	1866	1392	4938	138	48	960	483	1656	3099	2876	0.88
3	108	78	1560	1596	1296	4452	110	85	1700	1869	1320	4889	132	49	980	623	1584	3187	2953	0.90
4	98	79	1580	1738	1176	4494	98	79	1580	1875	1176	4631	118	50	1000	492	1416	2908	2715	0.90
5	108	78	1560	1596	1296	4452	110	81	1620	1869	1320	4809	129	48	960	624	1548	3132	2905	0.87
6	97	75	1500	1464	1164	4128	99	81	1620	1737	1188	4545	124	44	880	627	1488	2995	2760	0.88
7	104	72	1440	1597	1248	4285	106	79	1580	1734	1272	4586	121	45	900	628	1452	2980	2757	0.90
8	88	70	1400	1605	1056	4061	89	73	1460	1879	1068	4407	104	38	760	499	1248	2507	2330	0.90
9	118	79	1580	1591	1416	4587	118	87	1740	1728	1416	4884	136	47	940	484	1632	3056	2855	0.89
10	119	92	1840	1590	1428	4858	122	90	1800	1863	1464	5127	135	57	1140	622	1620	3382	3166	0.91
Avg.	**104**	**77**	**1534**	**1625**	**1246**	**4405**	**105**	**81**	**1610**	**1830**	**1264**	**4704**	**123**	**46**	**922**	**559**	**1478**	**2959**	**2747**	**0.89**

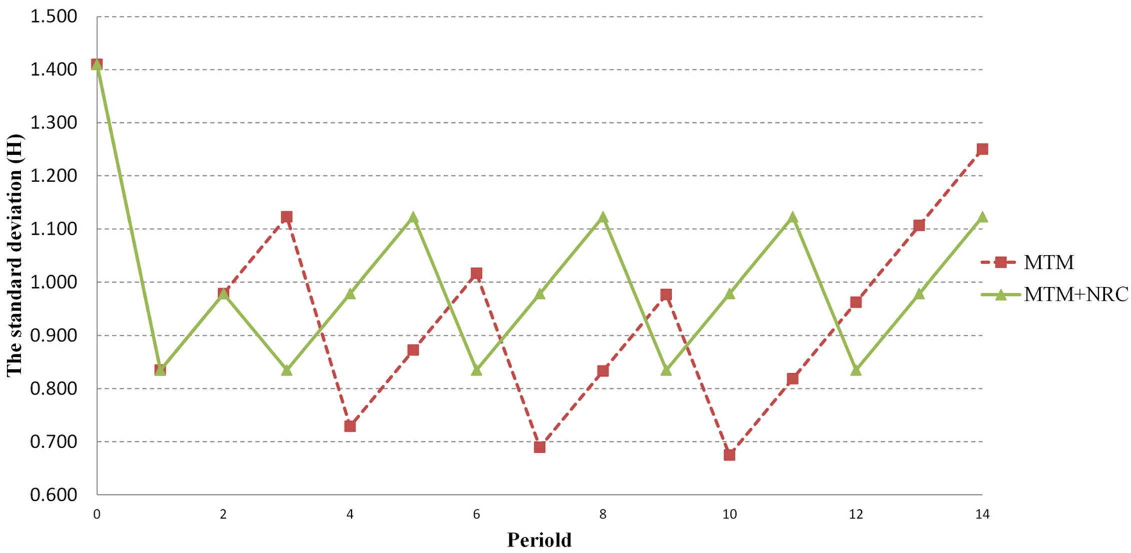

Fig. 7. The impact of NRC on section 196 in data Instance 10.

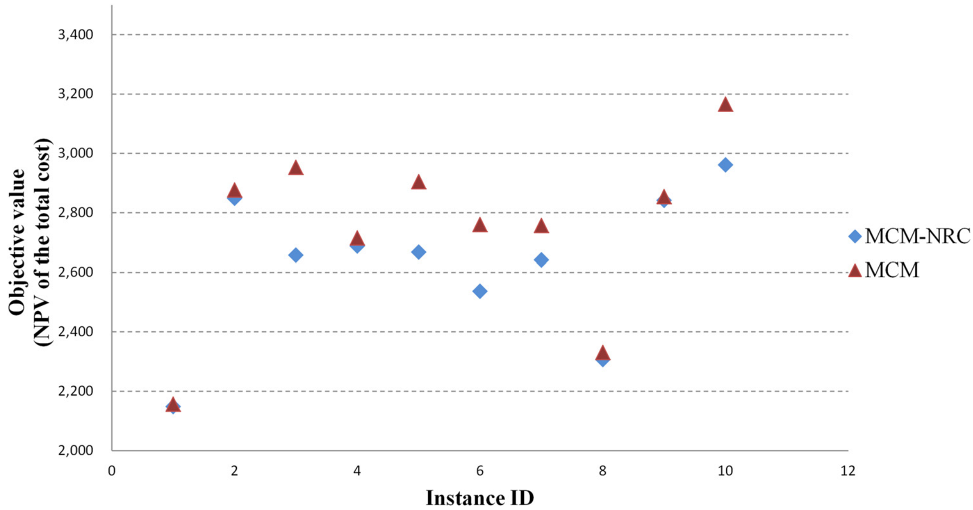

Fig. 8. The impact of NRC on the MCM model.

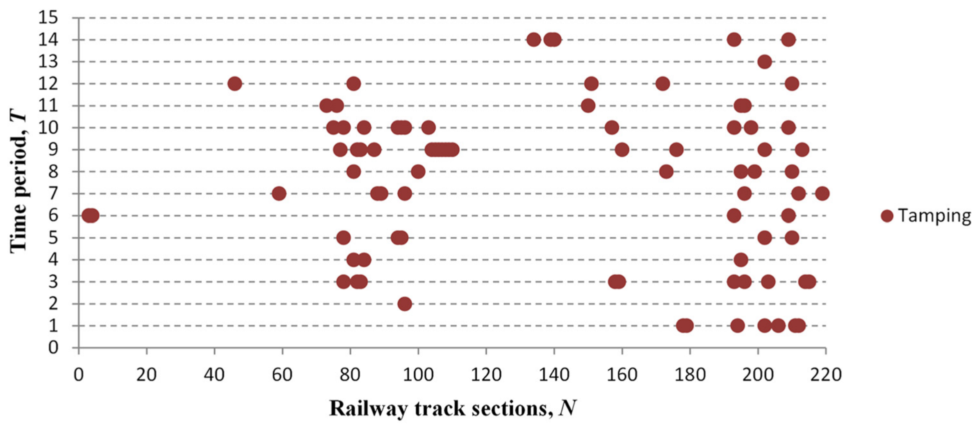

Fig. 9. The maintenance schedule for data Instance 1 obtained by MTM+NRC.

number of tamping operations is given by the results of MTM+NRC and MCM-INT. In both models, the new recovery constraints are considered and the interest rate is ignored. Figs. 9 and 10 depict the tamping schedules provided by both models for data Instance 1. Most of the tamping operations are applied on discrete individual sections by MTM+NRC and on grouped consecutive sections by MCM-INT. Consequently, MCM-INT minimizes not only the tamping cost but also the machine preparation cost and driving cost, which account for half of the total cost (Table 2). Clustering the tamping operations leads to a reduced preparation cost and potentially a lower total cost. As shown in Table 2, the average number of performed tamping operations over ten data instances is 105 for

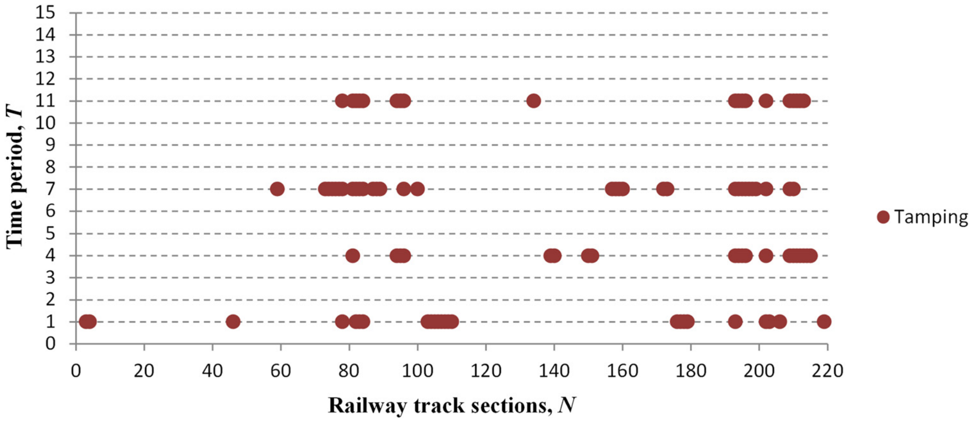

Fig. 10. The maintenance schedule for data Instance 1 obtained by MCM-INT.

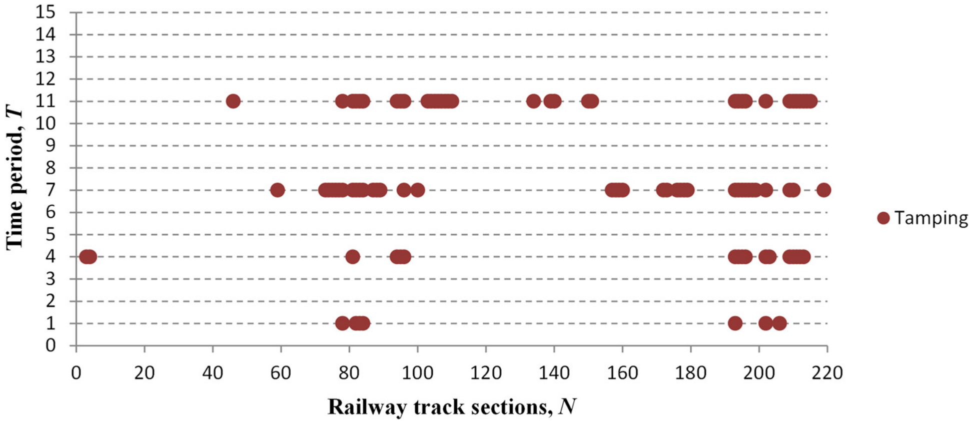

Fig. 11. The maintenance schedule for data Instance 1 obtained by MCM (with yearly interest rate 5 percent).

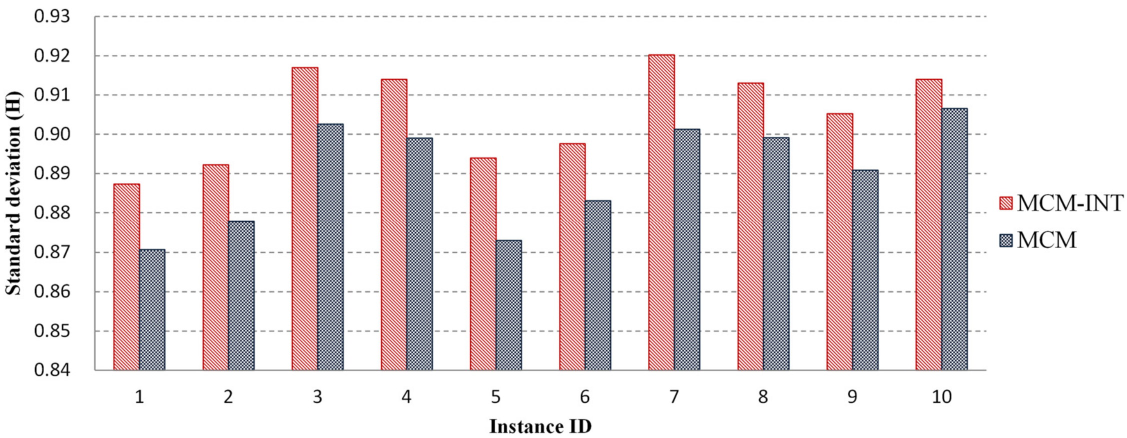

Fig. 12. The impact of minimizing NPC on the ending track quality (standard deviation at the longitudinal level).

MTM+NRC and 123 for MCM-INT. However, the actual maintenance cost of the schedule provided by the MTM+NRC is 59 percent more than that of the MCM-INT. This shows the importance of using minimization of the total costs as the objective function.

4.2.3. The effect of minimizing the NPC

The effect of minimizing the NPC can be seen by comparing the results of MCM-INT and MCM. As the periodical discount rate ($rT = \sqrt[4]{(1+r)} - 1 \approx 1.22$ percent), calculated based on the yearly interest rate ($r = 5$ percent), is a small number, the number of tamping operations and the number of preparations will not be affected by it. However, since the Present Cost (PC) of the same tamping cost is lower in a later period, the MCM will try to avoid unnecessary early tamping operations. The tamping schedules provided by MCM for data Instance 1 is illustrated in Fig. 11. Compared to the schedule provided by MCM-INT in Fig. 10, the schedule given by MCM pushes tamping operations to the latest possible time period before the standard deviation of the longitudinal level reaches the thresholds. For instance, the bundling tamping for Sections 3 and 4 has been scheduled to Day 360 in the MCM solution instead of Day 90 in the MCM-INT solution. Due to Eq. (1), avoiding unnecessarily early tamping can possibly lead to a better track quality at the end of the planning horizon of 14 quarters. Fig. 12 shows the

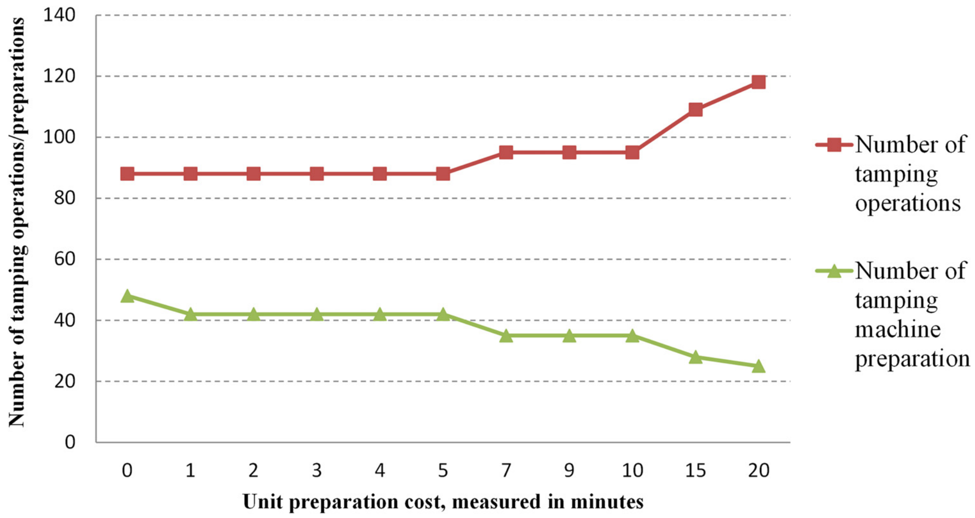

Fig. 13. The number of tamping operations and preparations as a function of the preparation cost.

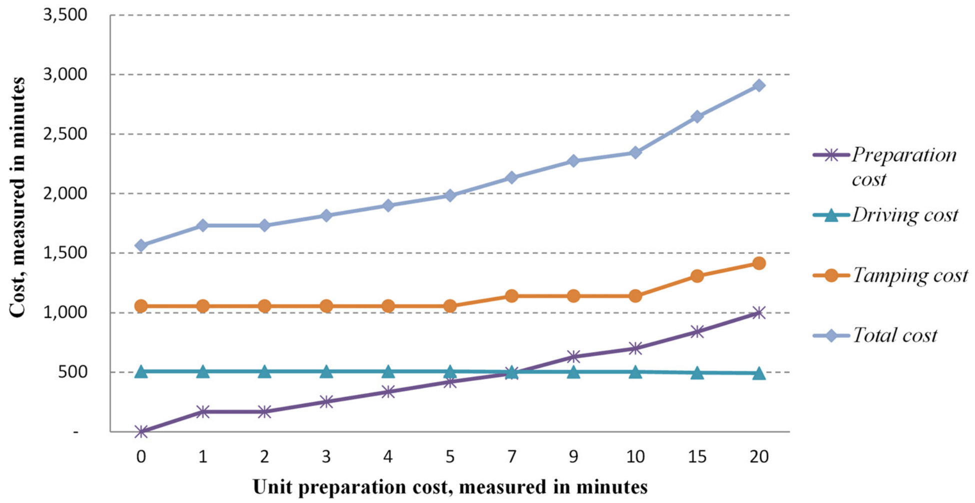

Fig. 14. The cost as a function of the preparation cost.

average ending quality over all sections by both models on each data instance. The ending quality has been improved by 2 percent on average by minimizing the NPC.

4.2.4. Sensitivity to the machine preparation cost

To show the sensitivity of the solution to the machine preparation cost, the MCM model is tested on data Instance 1 with different input values of the machine preparation cost, ranging from 0 minute to 40 minutes. The results are given in Figs. 13 and 14. As can be seen from Fig. 13, when the unit preparation cost increases, the number of tamping preparations reduces in order to reduce the total preparation cost. Intuitively, there are two ways to reduce the number of preparations. The first way is to group the existing tamping operations, e.g., tamping two consecutive sections in one period instead of tamping the two sections separately in two periods. This is what happens when the preparation cost is increased from 0 minute to 1 minute. The second way is to tamp all the sections lying between the two sections that should be tamped at the cost of increased number of tamping operations. This is what happens when the preparation cost changes from 11 to 12 minutes, 23 to 24 minutes and 35 to 36 minutes. Fig. 15 illustrates the costs of two plans when the preparation cost is 12 minutes. Plan TTT (Tamping-Tamping-Tamping) is cheaper than TDT (Tamping-Driving-Tamping) even though it requires one more tamping operation. Fig. 14 depicts how the different cost components and the total cost change as the preparation cost increases. The total cost increases almost linearly as the preparation cost increases.

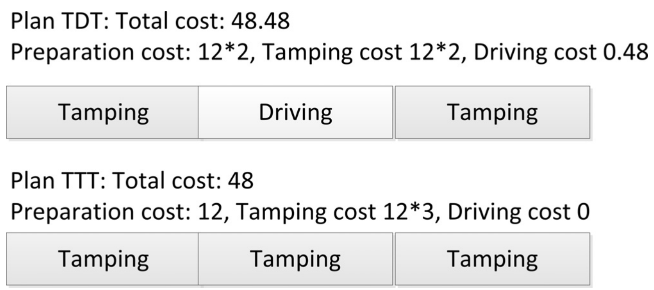

Fig. 15. Example of the total cost when the preparation cost is 12.

5. Conclusion

This paper addresses the scheduling of preventive conditional-based tamping maintenance, which is applied on the railway tracks to correct the standard deviation of the longitudinal level for safety and comfort of passengers and freight. The objective of this work is to find the least-cost tamping plan for given railway tracks over a planning horizon (i.e. three to four years). Compared to the existing models in the literature, a number of practical issues are considered, including extra practical cost components (preparation cost and driving cost), the time value for costs (through NPC) and a more realistic estimation of the tamping recovery.

As a result hereof a mixed integer programming formulation for this problem has been presented and tested on real-life data collected from the Danish railway corridor between Odense and Fredericia. Specifically five various model runs have been depicted and investigated bench marked to currently existing models from literature. Therein computational results show that it is important to consider extra cost components as they account for half of the total cost. The schedule obtained by minimizing the number of tamping operations is in fact 59 percent more expensive than the schedule given by minimizing the total cost. It is also shown that without the extra constraints on the tamping recovery, the total cost is under estimated by up to 10 percent. By minimizing the NPC, unnecessary early tamping operations are avoided and the final track quality at the end of the planning horizon is improved by 2 percent on average without extra cost.

This work can be extended in several directions in the future. Firstly, a heuristic or meta-heuristic algorithm that can provide fast quality solution to a large-scale track network could be included if the network should be extended further. Secondly, a more comprehensive forecast on the track degradation instead of the linear function used in this work can be investigated and integrated in the planning. Thirdly, extra decisions on track renewals can be introduced to provide a more economic overall solution. This is not a trivial task due to the high complexity of the combined renewal and tamping scheduling.

Acknowledgments

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Paper 2

A phase-based decision support system for railway preventive condition-based tamping

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Phase-based decision support system for optimizing railway preventive condition-based tamping

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The paper analyses how methods from Operations Research can support the decision for the scheduling problem of railway preventive condition-based tamping. A Phase-based Decision Support System is introduced to support railway infrastructure managers to optimize the tamping schedule for a given railway track over a fixed planning horizon. Four Mixed Integer Linear Programming models are formulated in three phases, i.e. a technical optimization phase, an economic optimization phase and a constrained optimization phase, with different focuses. The Phase-based Decision Support System is tested on a Danish railway track between Odense and Frederica with 57.2 km of length. The understanding for tamping optimization is improved through the new phase-based decision support system with a 40% reduction on total cost compared to the existing literature. It shows that the proposed system has a great potential to support railway tamping decisions in practice.

Keywords: Phase-based Decision Support System, Mixed Integer Linear Programming, Railway preventive condition-based tamping.

1. Introduction

For modern railways, maintenance is critical for ensuring safety, train punctuality and overall capacity utilization. The railway maintenance cost in Europe ranges between 30,000 - 100,000 Euro per track-km per year (*Jovanovic (2004)*). Appropriate planning for the railway maintenance to improve the track conditions is necessary because minor track irregularities on the geometry position can reduce the passenger comfort and evidently increase the wear on the various track components, ultimately causing train delays in a long term (*Zoeteman (2001)*). Concurrently major irregularities resulting in the geometry position can cause serious safety problems such as derailment *(Esveld (2001); Rail Net Denmark (2013))*. Accordingly, the European standard EN13848-5 has defined threshold limits for the track geometry positions to ensure safety and comfort for passengers (and goods).

To maintain track geometry positions under certain thresholds (also called conditions), condition-based tamping, as the most important track quality control, is required to be implemented on ballast tracks *(Esveld (2001))*. Tamping is expensive and it has an enormous pressure from the current tamping budget. To reduce the maintenance expenditure, several research papers seek to minimize tamping cost whilst remaining within the threshold limits of the track geometry position *(Vale et al. (2012); Uzarski & Mcneil (1994); Kong & Frangopol (2003); Macke & Higuchi (2007))*. Unfortunately, the gap between practitioners and academia have for this instance been wide, where particularly railway infrastructure managers (IMs) have difficulty to understand and implement the proposed methodological approaches, which is illustrated as An Academic Method approach in Figure 1. IMs have three main problems: 1) when too many impact-factors are involved in one comprehensive method, the output solution is very difficult to understand, evaluate and communicate in practice. 2) The typical academic approach lacks the functionality for expert adjustments, which is equally important as the computer method for scheduling tamping. The expert experience is necessary to ensure the feasibility of the computer generated solution, especially to balance the factors that are not formulated into the model. For instance, the planning administration cost (hiring planners and renting office to schedule tamping) is one of impact facts influencing the total tamping expenditure. However, it is difficult to define and include into an optimization model. A solution without considering this could result in a complex tamping schedule, which leads to a high demand on machine, and labour planning. Expert adjustment can avoid those potential problems. 3) Instead of getting only one optimal solution, IMs prefer to have a list of solutions with different pros and cons to compare and make decisions.

To overcome these problems, this paper seeks to formulate a Phase-based Decision Support System (PDSS) where a systematic phase-based framework is established to support decision-making. The proposed PDSS builds three phases to optimize tamping maintenance symmetrically, illustrated as the second approach in Figure 1. Firstly, a technical optimization is applied to identify the tamping needs purely from the technical aspect. The locations and time periods, where tamping operations are needed for the given tracks, are identified via the threshold-based principal. Secondly, tamping related costs are added to generate the optimal tamping solution with a lower cost. Finally, other constraints and adjustment parameters are taken into account for railway experts to adjust the optimal solutions and seek for other suitable solutions. Through the phase-based approach, the understanding for tamping optimization can be improved. Railway experts can participate the tamping scheduling from an early stage, evaluating and adjusting the outputs.

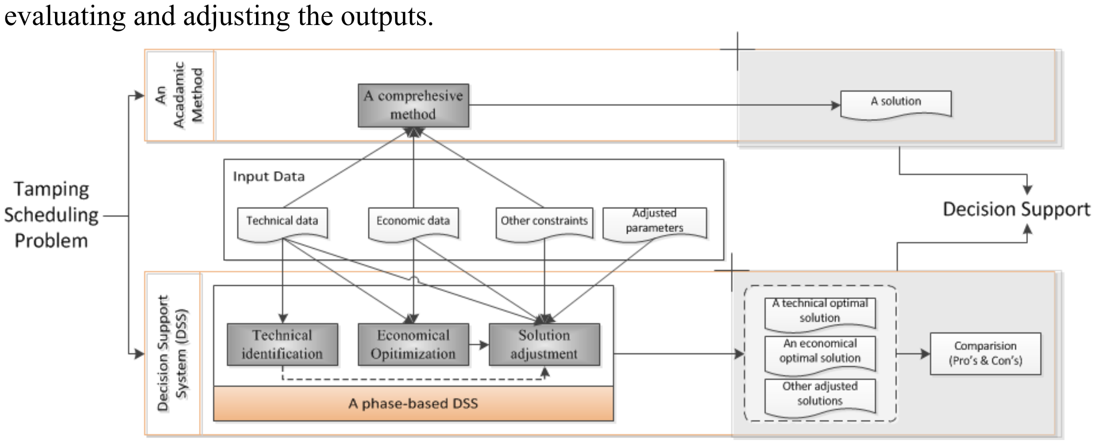


Figure 1: Above: A traditional approach, where all the impacted factors are included into one comprehensive model, from which only one best solution is generated. Below: The Phase-based Decision Support System, where the input data was divided into technical data, economic data, and other constraints & adjusted parameters. The tamping problem is solved in three optimization phases accordingly. A comparison report with a pool of solutions are generated to support decision-making

The remainder of the paper is organized as follows. Section 2 introduces railway tamping, the tamping scheduling problem and technical challenges. Section 3 reviews related literature and Section 4 presents the proposed PDSS and the mathematical models. Section 5 applies the proposed PDSS to a railway corridor in Denmark, after which a discussion and the results are presented in Section 6. Finally, Section 7 concludes the findings and envisions future research directions.

2. Tamping for Railway Tracks

Railway tamping operations can be explained as so-called compaction of the ballast in the railway track to increase the supportive effect from the ballast on the sides of and under the sleepers. The tamping vehicle has a tamping tool that consists of claws of picks that are inserted in the ballast on each side of the sleeper, after which the picks are vibrated, creating small movements in the ballast bed, which adjusts the position of the individual aggregates to reduce cavities. During the tamping process, the machine is collecting geometric information to the measuring system, which is controlling the gripping devices pulling the rails so that the correct horizontal and vertical position is restored *(Esveld (2001))*.

2.1 Type of condition-based tamping

Condition-based tamping is a maintenance strategy that monitors the condition of the track (evaluated by a certain threshold limit) to decide the overall tamping schedule. Two types of condition-based tamping are carried out regularly: Corrective Condition-based Tamping (CCT) and Preventive Condition-based Tamping (PCT). CCT is implemented to fix functional errors by which the safety related risks could occur such as derailment. Only implementing CCT will result in losing control of the track quality, therefore PCT, on the other hand, is also performed beforehand to decrease the probability of damaging railway tracks. Practical experiences showed that it is not possible to reduce costs for CCT due to the strict railway safety rules and that the functional errors are not predictable in terms of exact occurring location and time *(Banedanmark (2013))*. Therefore, this paper only focuses on the PCT, and particularly for the open tracks (not the railway stations).

2.2 The planning challenges

Preventive condition-base tamping is a complex and critical task particularly difficult to plan and execute. There exist mainly three challenges: C1) the prediction of track geometry changes over time. It includes the track geometry degradation and the recovery by tamping. The track geometry positions are impacted by many factors, such as subsoil condition, track components, rolling stocks, previous maintenance, and climatic conditions. There have been several research studies conducted within track degradation and tamping recovery however there are no standard methods widely implemented. C2) tamping budget and track possession. They are important and challenging as to ensure the feasibility of the tamping schedule as well as the train operation during the tamping process. C3) other operational limitations. A continuous action tamping machines for PCT have several limitations. Among others, it is not allowed to start/stop in a transition curve, which is a mathematically calculated curve on the railway track designed to prevent sudden changes in lateral acceleration (*UIC (2008))*. If a tamping section starts/stops inside a transition curve, the extended-tamping is required also for the connected section.

3. Literature review

Research on the topic of railway preventive maintenance has benefited from several aspects. One aspect is developing railway maintenance policy at the strategic level. Literature in this area focus on the Life Cycle Cost (LCC) *(Veit (2006); Zoeteman (2001))*, discussing how to balance maintenance and renewal to reduce average yearly spending (LCC annuity) for railway tracks. Track quality was formulated as a general concept of asset deterioration over time and the calculations were carried out in certain tools but without involving any mathematical optimization model. The mathematical programming was instead widely applied at the operational level e.g. solving the Preventive Maintenance Scheduling Problems (PMSP). *Budai and Dekker (2002)* showed that the preventive railway maintenance works are carried out in most countries during train service. To assign the given maintenance works to track possessions (free time intervals in train timetable), either an Operation Research optimization model or a timetabling software is implemented to solve the conflicts between train operations and track maintenance (the planning challenge C2). The preventive maintenance tasks and train timetables were (re-)scheduled to, e.g. minimize the track possession duration *(Budai & Dekker (2004); Famurewa et al. (2015))*, minimize the train delays *(Higgins et al. (1999))*, maximize the improvement of track irregularities *(Oyama & Miwa (2006))*, or minimize the disruption and costs *(Boland et al. (2013); Zhang et al. (2013); Peng et al. (2011); Gustavsson et al. (2014))*. Meanwhile from another perspective in PMSP, several literature attempted to group the maintenance works by time-space dimensions to save cost. For instances, *vanDijkhuizen & vanHarten (1997)* considers a clustering problem for frequency-constrained maintenance jobs in an infinite-horizon setting, whereas *Wildeman et al. (1997)* presents a rolling-horizon approach to group maintenance activities on a short-term basis. The similarity in PMSM is that the preventive maintenance jobs are given with certain durations and fixed time windows. The track quality prediction and tamping machine limitations are not included.

The present paper aims to optimize the preventive maintenance work from a higher planning level. This study is to seek tamping schedules in terms of the location and time windows to execute preventive condition-based tamping based on the given thresholds. The most relevant research for this problem are provided by *(Vale et al. (2012), Vale & Ribeiro (2014) and Wen et al. (2016))*. Two former papers built Mixed Integer Linear Programming (MILP) models to minimize the total number of tamped sections over a given planning horizon. The track deterioration rate is assumed constant in *(Vale et al. (2012))*, whereas, it is simulated by Monte Carlo techniques in a stochastic process in *(Vale & Ribeiro (2014))*. Both papers addressed the planning challenges C1 and C3. Later on, *Wen et al. (2016)* extends the problem by including a number of additional important practical factors such as the extra cost components, tamping machine characteristics and a more realistic tamping recovery estimation. The result shows that optimizing the Net Present Costs (NPC), the sum of the present value of all costs, can reduce tamping expenditure up to 50% and improve the track quality at the end of the planning horizon comparing to *(Vale et al. (2012))*. All three papers implemented track quality control on specific index of track geometry position at one dimension (1D) i.e. the standard deviation of longitudinal level (SD_{LL}). This paper seeks to extend the model in *(Wen et al. (2016))* in two areas, including the track geometry quality control on both horizontal and longitudinal dimensions (2D) to better describe the planning challenge C1 and solve it correspondingly; at the same time introducing the possession constraints to be able to solve the planning challenge C2, and remaining the same constraints for the planning challenge C3 as in *(Wen et al. (2016))*. Thus, new MILP models can solve all three main planning challenges.

4. Problem Formulation

The problem of consideration is an optimization of preventive condition-based tamping maintenance for a given railway track over a planning horizon. The railway tracks are discretized into a number of consecutive sections of the same length. The tamping machine travels on top of the railway track from one end to the other and applies tamping operation on the sections if necessary. The track quality of each section is measured by its standard deviation SD_{LL} and SD_{HA}. The same as in *(Wen et al. (2016))*, the track geometry degradations are regarded to be linear over time. The initial quality, degradation rate and threshold value of each section are assumed to be known. Tamping decision (tamping time and tamping locations) is based on the condition-based principal, where track degrades continuously and are restored by a tamping before exceeding the thresholds.

4.1 Phase-base Decision Support System

A Phase-based Decision Support System (PDSS), illustrated in Figure 2, has been formulated to provide the decision support.

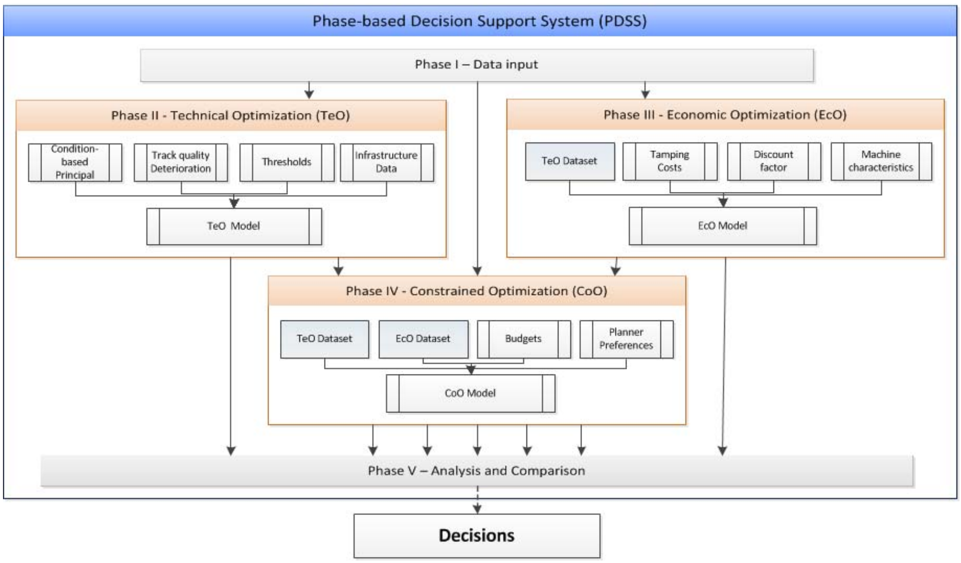


Figure 2: The phase-based decision support system

The proposed PDSS contains five main phases: 1) Data input, 2) Technical Optimization (TeO), 3) Economic Optimization (EcO), 4) Constrained Optimization (CoO) and finally 5) Analysis and comparison. MILP models are formulated in Phase TeO, EcO and CoO. Technical related data including track quality deterioration, threshold limits and infrastructure data. The aim of TeO is to identify the minimum tamping requirements from a pure technical aspect. Economic related data including the different tamping costs and tamping machine characteristics are used together with the technical related data to generate an economical optimal tamping schedule in the EcO phase, covering the same tamping needs with the minimum total costs. In the CoO phase, tamping budget, planner preferences together with the output from EcO are taken into account to adjust and reschedule the tamping plans. Finally, in Phase 5, the generated tamping schedule options are compared. As an output from the proposed PDSS, a set of tamping schedules are generated to support the tamping decisions. The rest of paper will focus on the three optimization phases in PDSS. The data input phase and the analysis & comparison phase are mentioned only in the case experiment in section 5.

4.2 The TeO Model

The mathematical model in TeO, denoted as *the TeO Model*, seeks the minimum number of tamping actions, presented in the objective function (1).

The TeO Model:

$$\min \sum_{t\in T}\sum_{i\in N} df^{t} \cdot x_i^t \tag{1}$$

For each track section $i \in N$, and time period $t \in T$, a binary variable x_i^t equals to 1 if section i is tamped at time period t, and 0 otherwise. A discount factor df is applied to ensure a proper backcasted benefit of all future related tamping activities. By multiplying df, tamping can be scheduled as late as possible during the minimization in the TeO model.

$$\sigma_i^0 = l_i \qquad \forall i \in N \tag{2}$$

$$\sigma_i^{t-1} + d_i \le e_i \qquad \forall i \in N, t \in T \tag{3}$$

$$\sigma_i^t = \sigma_i^{t-1} + d_i - w_i^t \qquad \forall i \in N, t \in T \tag{4}$$

Track quality is measured by the standard deviation of the longitudinal level SD_{LL} and the standard deviation of the horizontal alignment SD_{HA}, simultaneously. Constraints (2-4) keep track of SD_{LL} at each section in each period. Constraints (2) initialize SD_{LL} and Constraints (3) enforce the bound values. Constraints (4) set the quality of section i at the end of period $t \ge 1$ (σ_i^t) based on the quality at the end of the previous period (σ_i^{t-1}), the degradation within one period (d_i), and the tamping quality recovery (w_i^t).

The track quality recovery by tamping depends on a set of different factors. Firstly, there is a linear relationship between the quality recovery and the quality before tamping. The International Union of Railways (UIC) denotes that if the current SD_{LL} before tamping is σ, the tamping recovery can be no more than ($Y(\sigma) = a \cdot \sigma + b$), where a and b are given parameters and $Y(\sigma)$ is the Quality-dependent recovery upper bound (r), illustrated as the first tamping at time period 3 in Figure 3. Secondly, the recovery is also dependent on the preceding tamping operation because tamping itself may crash the ballast, which is the main factor of track stability as shown in many previous studies *(Zoeteman (2001); Esveld (2001); Veit (2006); UIC (2008))*. Therefore, the resultant quality of the present tamping can never be better than the one achieved by the preceding tamping. This maximum recovery bounded by the preceding tamping is referred to Tamping-dependent recovery upper bound (s). The tamping recovery is set to the smaller value of the two above-mentioned upper bounds in the TeO model, illustrated as the second tamping at time period 4 in Figure 3, where s is smaller than r and therefore it is chosen as the tamping recovery.

$$w_i^t = \min\left(r_i^t, s_i^t\right) \cdot x_i^t \qquad \forall i \in N, t \in T, t > 0 \tag{5}$$

$$r_i^t = \max\left(a \cdot (\sigma_i^{t-1} + d_i) + b, 0\right) \qquad \forall i \in N, t \in T, t > 0 \tag{6}$$

$$s_i^t = \sigma_i^{t-1} + d_i - u_i^t \qquad \forall i \in N, t \in T \tag{7}$$

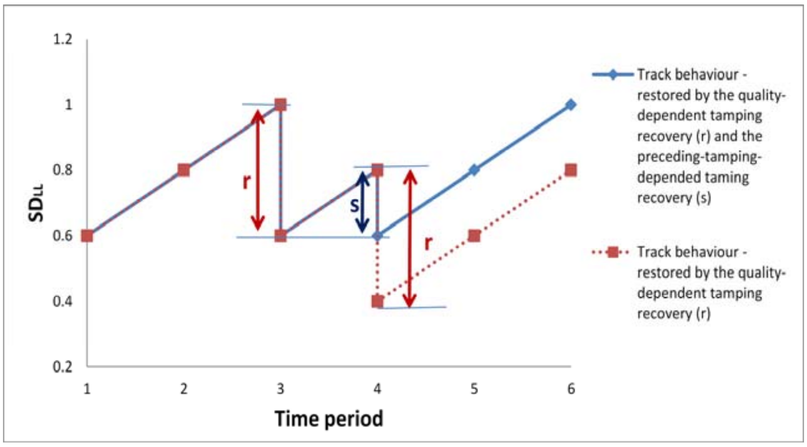


Figure 3: The quality recovery by tamping. The track geometry is restored by the quality-dependent recovery (r) in period 3, and restored by the preceding-tamping-depended recovery (s), the smaller value between r and s, in period 4.

Constraints (5-7) determine the *SDLL* recovery by tamping (w_i^t). If the section is not tamped where $x_i^t = 0$, the quality recovery (w_i^t) is set to 0; Otherwise it is set to the smaller value of r_i^t and s_i^t. Constraints (6) express the linear relation between r_i^t and the current track quality ($\sigma_i^{t-1} + d_i$) and ensure no negative recovery achieved by tamping. Constraints (7) define s_i^t, setting it to the difference between the quality before tamping ($\sigma_i^{t-1} + d_i$) and the minimal *SDLL* (u_i^t) that can be achieved by tamping.

$$u_i^0 = o_i \qquad \forall i \in N \tag{8}$$

$$u_i^t = \max\left(u_i^{t-1}, \sigma_i^{t-1} \cdot x_i^{t-1}\right) \qquad \forall i \in N, t \in T \tag{9}$$

Constraints (8) initialize the value of u_i^t for section i in period t. Constraints (9) determine the value of u_i^t based on u_i^{t-1} and x_i^{t-1}. If $x_i^{t-1} = 0$, u_i^t is set to u_i^{t-1}. Otherwise, it is set to σ_i^{t-1}, the resultant *SDLL* of the tamping in period $(t-1)$.

$$\hat{\sigma}_i^0 = \hat{l}_i \qquad \forall i \in N \tag{10}$$

$$\hat{\sigma}_i^{t-1} + \hat{d}_i \le \hat{e}_i \qquad \forall i \in N, t \in T \tag{11}$$

$$\hat{\sigma}_i^t = (\hat{\sigma}_i^{t-1} + \hat{d}_i) \cdot (1 - x_i^t) + \hat{v}_i \cdot x_i^t \qquad \forall i \in N, t \in T \tag{12}$$

$$x_i^t \in \{0,1\} \qquad \forall i \in N, t \in T \tag{13}$$

$$\sigma_i^t, \hat{\sigma}_i^t, w_i^t, \hat{w}_i^t, r_i^t, u_i^t, s_i^t \geq 0 \qquad \forall i \in N, t \in T \tag{14}$$

Constraints (10-11) define the same track quality control as Constraints (2-3), but on *SD_{HA}* at horizontal alignment. Constraints (12) define that the horizontal resultant quality ($\hat{\sigma}_i^t$) on *SD_{HA}*. Through a tamping operation, it is restored to a certain value ($\hat{v}_i$) according to the previous investigation carried out in 70s from the former Office for Research and Experiments (ORE) *(Andrade & Teixeira (2015))*. Finally, all variables are defined by Constraints (13-14).

In order to implement the tamping at the exact time-location points suggested by the TeO model, the TeO+ model is formulated in the TeO phase with the consideration of the tamping machine limitation on transition curve(s).

The TeO+ Model:

Objective Function (1)

Subject to:

Constraints (2 -14)

$$x_j^t \geq x_i^t \quad \forall i \in N, j \in I(i), t \in T \tag{15}$$

Constraints (15) make sure that extended-tamping take place for the sections linked by transition curve(s) as illustrated in the Section 2.2. For each track section $i \in N, I(i) \in N$ denotes the set of consecutive indexes of track sections linked by transition curve(s).

4.4 The EcO Model

After identifying the minimal tamping activities in the TeO phase, the economic factors, i.e. three types of costs related to the tamping machine characteristics of warm-up, tamping, ramp-down and driving, are implemented in the EcO phase to generate an optimal tamping schedule covering the same tamping needs, but at the same time achieving the least Net Present Costs (NPC), the sum of the present value of all costs. The mathematical model in EcO, denoted as *the EcO Model*, is presented as follows.

The EcO Model:

$$\min \sum_{t \in T} \left(\sum_{i \in N} \left(c \cdot x_i^t + k \cdot y_i^t \right) + f \cdot z^t \right) \cdot df^t \tag{16}$$

Subject to:

Constraints (2 -15)

$$y_1^t \geq x_1^t \qquad \forall t \in T \tag{17}$$

$$y_i^t \geq x_i^t - x_{i-1}^t \qquad \forall i \in N, t \in T, i \geq 2 \tag{18}$$

$$x_i^t \leq z^t \qquad \forall i \in N, t \in T \tag{19}$$

$$y_i^t, z^t \in \{0,1\} \qquad \forall i \in N, t \in T \tag{20}$$

The objective function (16) minimizes NPC over the planning horizon. A fixed driving cost (f) is for a tamping machine to drive through all the sections if tamping takes place in a certain period *t*. An extra tamping cost (c), is for tamping one section and an extra preparing cost (k) is for warming up the tamping machine before tamping and ramping down the tamping machine after tamping. The binary variable z^t equals to 1 if any tamping takes place in period *t* and 0 otherwise. Finally, the binary variable y_i^t equals to 1 if the tamping machine is starting up from section i at time period *t*, and 0 otherwise. The same as *the TeO Model*, *df* is applied to push tamping operations to the latest possible time via the NPC minimization.

Constraints (17) and (18) ensure that tamping machine executes a warm-up before implementing tamping. y_i^t is set to 1 if section $(i-1)$ is not tamped and section *i* is going to be tamped at time period *t*. Constraints (19) set z^t to 1 if tamping takes place at any section in period *t*. At the end, the additional binary variables are defined by Constraints (20).

4.5 The CoO Model

In the CoO phase, the other factors, such as tamping budgets, planner preferences on track possessions, are taken into account to evaluate and adjust the optimal solution from EcO. The purpose is to generate the alternative tamping schedule options to ensure the feasibility corresponding to the other actual planning requirements. The mathematical model in CoO, denoted as *the CoO Model*, is formulated as follows.

The CoO Model:

$$\min \sum_{t \in T} \left[\left(\sum_{i \in N} \left(c \cdot x_i^t + k \cdot y_i^t \right) + f \cdot z^t \right) \cdot df^t + p \cdot \left(1 - \theta_i^t \right) \right] \tag{21}$$

Subject to:

Constraints (2-15, 17-20)

$$\sum_{i \in N} \left(c \cdot x_i^t + k \cdot y_i^t \right) + f \cdot z^t \leq bT \qquad \forall i \in N, t \in T \tag{22}$$

$$\sum_{t \in Y(t)} \left(\sum_{i \in N} (c \cdot x_i^t + k \cdot y_i^t) + f \cdot z^t \right) \leq bY \quad \forall i \in N, t \in Y(t), Y(t) \in T \tag{23}$$

The objective function (21) minimizes the summary of NPC and the penalty of track possession. The later cost is calculated by the penalty unit price (p) multiplying the coefficients $(1-\theta_i^t)$, where $(\theta_i^t \in R\{0,1\})$ is the possession parameter used to set the percentage of working possession paid by the other work. For example, if it has been decided by the catenary and power supply work that the normal train traffic will not operate in period $t' \in T$, operating tamping maintenance simultaneously in that period will not cause any penalty. Therefore, the IMs can set the preference factors $\theta_i^{t'}$ to 1 at time period t', and 0 at the other periods $t \in \{T \backslash t'\}$ for all the sections. When the penalty is high enough, the tamping will be scheduled to the other periods. The possession penalty is only a punishing monetary value (not a real cost), the discount factor (*df*) is thus not applied to it.

Constraints (22-23) set two types of budget: static budget and rolling budget, respectively. Static budget (*bT*) is the upper bound of tamping expenditure for a single time period; while rolling budget (*bY*), also known as a continuous budget or a rolling horizon budget is the budget for a subset of time horizon. In practice, a homogeneous cycling tamping plan is much easier to understand and hence to implement. The new rolling budget provides the feature to find such a plan. The disadvantages of setting budgets, however are 1) there does not always exist a feasible solution within given budget restrictions, 2) the NPC of the total tamping cost could increase, and 3) longer computing time should be expected.

In this paper, all the longitudinal related constraints are taken from the previous study *(Wen et al. (2016))*. The horizontal related constraints (10-12), the rolling budget constraints (23), the planner preferences (21) and the set-up of phase-based framework are new contributions.

5. Case Experiments

This section introduces a Danish case study that is used to demonstrate the proposed phase-based decision support system (PDSS). The real-life data in terms of infrastructure layout, traffic, geometric quality surveys, and maintenance history have been collected from Banedanmark.

5.1 Background

The Danish railway corridor linking Odense to Fredericia (Od-Fa), with a length of 57.2 km, is a part of the busiest interregional main line connecting the four biggest cities in Denmark i.e. Copenhagen, Odense, Aarhus and Aalborg, as depicted in Figure 4. The Od-Fa corridor comprised of a double-track structure is heavily used by both national and international (Sweden - Germany) passenger and freight trains. In this experiment, the proposed PDSS is tested on its applicability only to the open track and moreover only on the right track of the double-track line because of the practical reason in Denmark i.e. a double-track corridor is considered as two separated single track projects for preventive tamping planning. The railway tracks are discretized into 220 consecutive sections. The planning horizon is set to 10 quarters.

Figure 4: The Od-Fa corridor on the Rail Net Denmark network (2014).

5.2 Initial track geometry quality and track degradation

The track quality is defined as the standard deviation at the longitudinal level (SD_{LL}) and the standard deviation at the horizontal alignment (SD_{HA}) in the wavelength interval (3-25 meters) for each track section of 200 meters. The SD_{LL} related data are collected from the historical measurements at Banedanmark between *March 19, 2007* and *November 26, 2012*, in which nine random measurements are taken as initial qualities SD_{LL} (σ_i^0) in the testing instances. The SD_{HA} related data are generated according to the correlation between SD_{LL} and SD_{HA} suggested by *(Andrade & Teixeira (2015))*. The threshold values for SD_{LL} and SD_{HA} are calculated from the maximum allowed speed according to the national Rail Standard BN1-38-4 (2011). Figure 5 shows the initial track quality of the longitudinal level taken from *November 26, 2012* used in Instance 1. The red lines represent the initial track quality (SD_{LL}); the blue dash lines indicate the corresponding thresholds. The average track degradation of the longitudinal level which has been prepared for every 90 days consequently depicting the so-called evolution of the track quality ($\Delta\sigma$) in Figure 5. The values were calculated empirically using the linear regression for each section.

5.3 Track alignment layout

Figure 6 shows the track alignment layout example from Odense to Tommerup, the second station located in Od-Fa corridor. The track sections highlighted in the yellow boxes in Figure 6 are the consecutive sections connected by transition curves. In such case, the tamping machine limitation needs to be considered when optimizing the tamping schedules. The bundling tamping will be implemented for the section group when anyone of them needs a tamping.

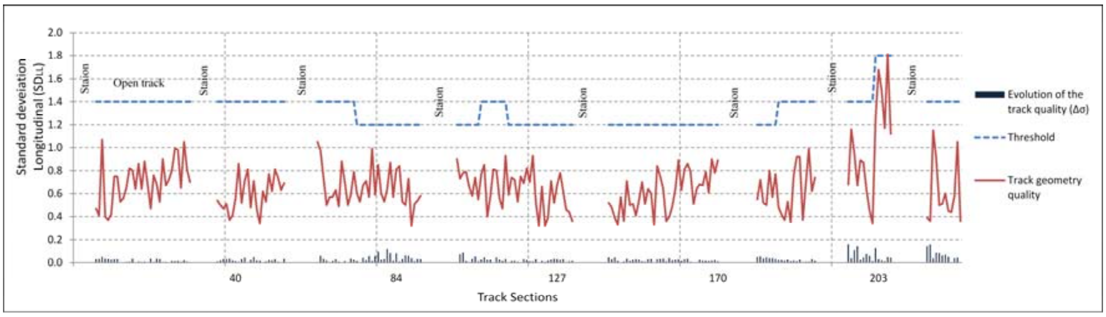


Figure 5: The initial track quality, the thresholds and the track degradations in the Od-Fa Corridor.

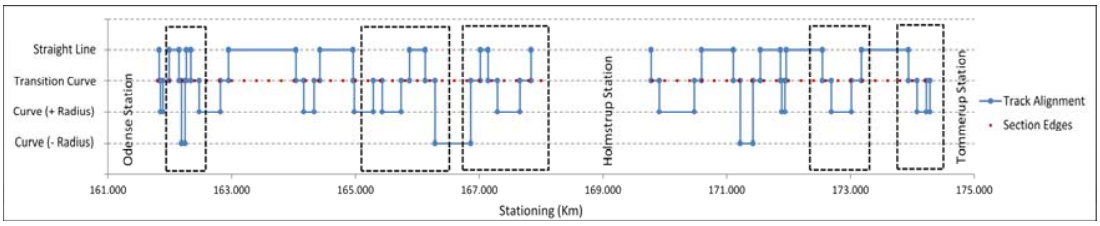


Figure 6: The track alignment layout (Odense - Tommerup)

5.4 Quality recovery after tamping

According to the Danish tamping improvement project *(de Saint-Aubain et al. (2012)),* the improvement of the quality-dependent recovery caused by tamping at the longitudinal level has been determined in Equation (24). Meanwhile the track quality at the horizontal alignment will be restored to a given value after a tamping.

$$w_i^t = 0.63 \cdot \sigma_i^t - 0.26 \tag{24}$$

5.5 Tamping Costs

In this study, tamping cost is measured by operating time of the tamping machine. The data are as follows *(Banedanmark (2013))*:

- 12 minutes to tamp a section of 200 meters (tamping speed is about 1 km/h)
- 20 minutes to warm up/ramp down the tamping machine before/after tamping
- 0.48 minutes to drive through a section of 200 meters (driving speed is about 25 km/h)
- Discount factor (*df*) is 1.23%, calculated according to the yearly interest rate 5%.

6. Results and Discussions

The proposed MILP models in PDSS are solved by CPLEX version 12.6.0.0. The results of the Danish case study are shown in Table 1 and Table 2. The models include: 1) TeO, 2) TeO+, 3) EcO and 4) CoO. The outputs presented in Table 1 and Table 2 contain: number of tamping sections (T_s), number of tamping periods (T_t), preparation costs (C_p), driving costs (C_d), tamping costs (C_t), and Net Present Cost of the total costs (*NPV*). The costs are calculated for all the models for the comparison purpose. The average of nine instances are highlighted in the bottom row of Table 2.

Table 1. Tamping schedules generated from the PDSS

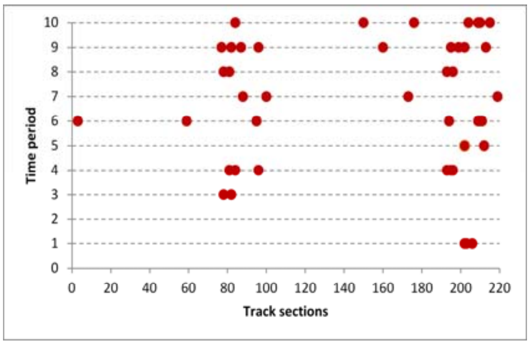
PDSS Models	Ts	Instance 1 Tt	C_t	C_p	C_d	NPV	%
TeO	44	9	523	780	1214	2482	178%
TeO+	50	9	600	780	1212	2591	186%
EcO	52	3	424	460	387	1391	100%
CoO1 (bT =420)	52	4	624	460	524	1526	110%
CoO2 (rT=540)	53	3	636	500	386	1442	104%
CoO3 (prefer: T = (4, 7))	53	3	636	500	386	1437	103%

Table 2. The results from PDSS

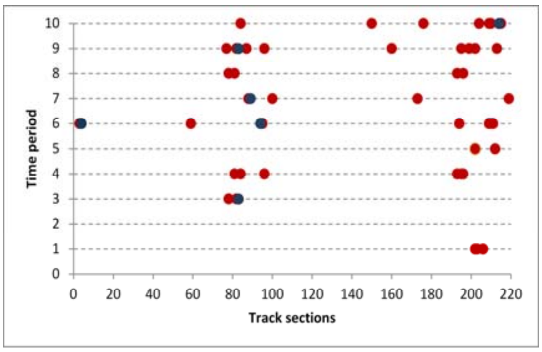
	TeO						TeO+						EcO					
Ins.	**T_s**	**T_t**	**C_t**	**C_p**	**C_d**	**NPC**	**T_s**	**T_t**	**C_t**	**C_p**	**C_d**	**NPC**	**T_s**	**T_t**	**C_t**	**C_p**	**C_d**	**NPC**
1	44	9	528	780	1214	2482	50	9	600	780	1212	2591	52	3	624	460	387	1391
2	64	10	768	1140	1342	2326	78	10	936	1140	1335	3388	87	3	1044	700	370	2021
3	62	10	744	1180	1343	3262	71	10	852	1120	1339	3260	83	4	996	680	509	2082
4	58	10	696	1100	1345	3106	68	10	816	1080	1340	3196	78	3	936	720	374	1940
5	59	10	708	1080	1344	3096	73	10	876	1080	1338	3272	82	4	948	720	510	2103
6	59	10	708	1140	1344	3155	65	10	780	1120	1342	3177	74	4	888	580	514	1884
7	57	10	684	1080	1345	3054	67	10	804	1060	1341	3195	74	3	888	680	376	1855
8	46	10	552	920	1351	2783	53	10	636	900	1347	2874	61	3	732	540	383	1583
9	67	9	804	1280	1203	3232	85	9	1020	1260	1195	3430	99	3	1188	780	364	2228
Av.	**57**	**10**	**688**	**1078**	**1315**	**3044**	**68**	**10**	**813**	**1060**	**1310**	**3154**	**77**	**3**	**920**	**421**	**421**	**1899**

6.1 The usage of the different phases in PDSS

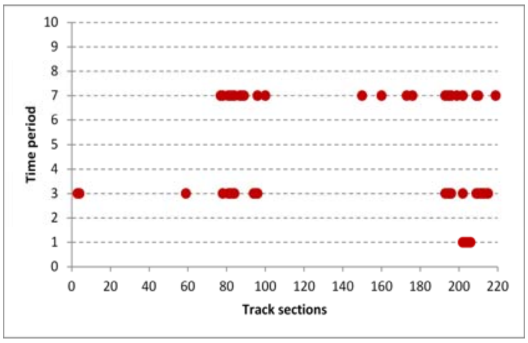
The tamping schedules for Instance 1 are shown in Table 1 and visualized in Figure 7. The red (and the blue) dots in Figure 7 illustrate the location and time to implement tamping operations. Figure 7a and Figure 7b show the tamping requirements and the corresponding tamping actions respectively, from the TeO phase. Figure 7c represents the economical optimal tamping schedule from the EcO phase, and Figures 7d-7f demonstrate the adjusted tamping schedules generated from the CoO phase.



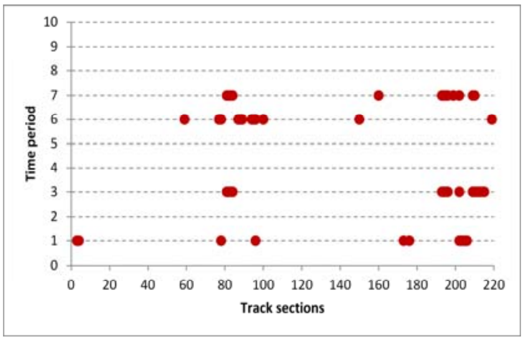
(a) TeO



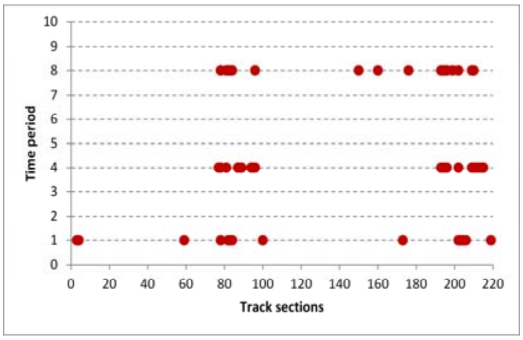
(b) TeO+



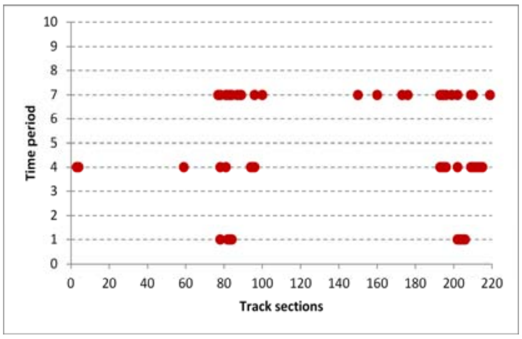
(c) EcO



(d) CoO with bT = 420



(e) CoO with rT = 540



(f) CoO with preferences at T = (4, 7)

Figure 7: Tamping schedules generated in the proposed PDSS (Instance 1)

Figure 7a shows the latest possible tamping time for each section from a pure technical point of view. The minimum total number of Tamping-Sections (*TS*) is 44 for the planning horizon of 10 quarters. Figure 7b considers the tamping machine limitation on the transition curve(s). Additional six tamping operations, highlighted in blue dots, are needed as well.

Figure 7c illustrates the most economical tamping schedule, where the total *NPC* is optimized. It can be seen that the EcO model clusters tamping operations in order to reduce the tamping machine preparation cost and the driving cost, which was neglected in the TeO and TeO+ model. Furthermore, the schedule provided by the EcO model is more practical and intuitive to be adopted, in the sense of reduced complexity for labour and machine scheduling.

Figure 7d and 7e illustrate how the static budget and the 3-quarter rolling budget affect the EcO solution. Figure 7d is obtained by adding a static budget of 7 hours' possession limit (minutes) to the EcO model. The EcO schedule in Figure 7c becomes no longer feasible due to the high investments in time $T = 4$ and $T = 7$. As a result, tamping operations take place in four batches instead (Figure 7d). Similar result can also be seen in Figure 7e, where a rolling budget of 9 hours is added to the EcO model.

Figure 7f shows another tamping schedule adjusted by infrastructure planner setting preferences. In this case, the unit penalty price (*p*) is set to 3 minutes to penalize taking the track possession for all sections in all the periods except $T = (4, 7)$. The tamping is then scheduled to period $T = (1, 4, 7)$ with an increased NPC (103%).

The planner preference is a soft adjust parameter comparing to the budgets that are treated as hard constraints. Because the tamping activities are not always scheduled to the preferred period. It depends on the values of the unit penalty price (p) and the values of preference factors ($\theta_i^{t'}$). Furthermore, the possession penalty (p) could also be set to other costs (or benefits) i.e. passenger travel time penalty. With new values of its coefficients ($1 - \theta_i^{t'}$), it can be used to adjust the tamping schedule to avoid the traffic peak periods.

6.2 The impact of static budget on tamping expenditures

Figure 8 presents the sensitivity analysis on the NPC changes caused by different static budgets in the EcO phase. Figure 8 moreover reflects the fact that giving a static budget, the tamping expenditures can increase substantially. When the static budget is extremely restrictive ($bT \leq$ 250 minutes), no feasible solution exits because the budget is not high enough to control the track quality under the thresholds. When the static budget is high enough ($bT \geq$ 700 minutes), it will not affact tamping schedules. Except for two extreme sides, total tamping expenditure rises exponentially with the reduction of the static budget. As when the static budget is set too tight, tamping are forced to split into more periods which is against the grouping and therefore cause an significant increase of the total cost. In practice, a static budget is still necessary to avoid a sudden cost overrun. However it is important to set the static budget in an appropriate range (e.g. 500 - 700 minutes in Figure 8) to avoid the additional costs caused by the budget.

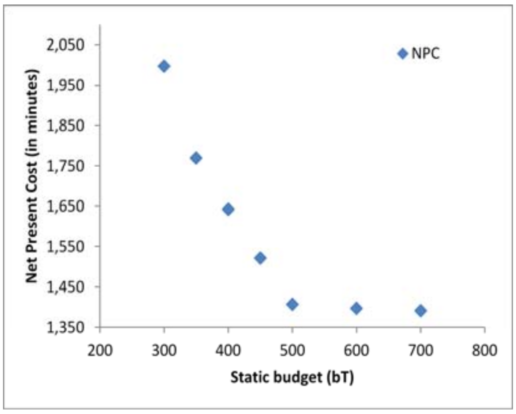


Figure 8: Impact of static budget on total tamping expenditure (Pareto front)

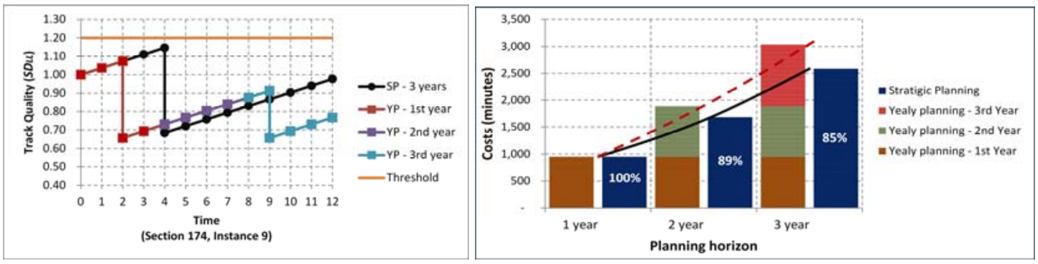
6.3 The advantage of strategic planning

Two tamping strategies, Yearly Planning (YP) strategy and Strategic Planning (SP) strategy, are compared in this analysis. The YP strategy is the common practice in the real world, where tamping is scheduled every year. For a 3-year planning problem, the YP strategy decomposes it into three 1-year planning problems and generates three tamping schedules; while the SP strategy optimizes tamping for the 3-year planning horizon instead. Table 3 reports the tamping expenditures generated by two planning strategies for ten instances. The first column indicates the instance number. The next six columns compare the *NPC* between the YP Strategy and the SP strategy. It can be seen that two strategies generate different *NPC*'s for the 2-year and the 3-year planning horizons.

Table 3. Yearly planning vs. Strategic planning

	NPC comparison in planning horizon T					
	T= 1 year		T=2 year		T= 3 year	
Instance	YP	SP	YP	SP	YP	SP
1	402	402	1270	1172	2365	2019
2	898	898	1902	1736	3027	2741
3	1068	1068	1924	1700	3197	2705
4	990	990	1931	1713	3019	2572
5	1056	1056	2011	1809	3203	2699
6	851	851	1794	1620	2904	2563
7	949	949	1806	1545	2995	2548
8	825	825	1682	1502	2752	2286
9	1121	1121	2176	1912	3453	2836
10	1346	1346	2366	2135	3462	2912
Average	**951**	**951**	**1886**	**1685**	**3038**	**2588**

The reason is that the SP strategy gives more flexibilities to cluster the tamping operations in the entire planning horizon. As the example presented in Figure 9a, the track behaviours for Section 174 clearly shows a cost saving in the SP strategy. The YP strategy forces two tamping at time $T = 2$ and $T = 9$. Whereas the SP strategy requires only one tamping. Finally, a fast run through all of the EcO models increasing the planning horizon to 3 years as demonstrated in Figure 9b, it can be seen that by implementing the SP strategy, the savings increases obtained by prolonging the planning horizon (11% for 2-year and 15% for 3-year, respectively).



(a) Track behavior comparison *(b) NPC comparison*

Figure 9: Yearly planning vs. Strategic planning

6.4 Sensitivity to track degradation rates

Figure 10 illustrates the sensitivity to the track degradation rates. The TeO model and the EcO model are applied on data Instance 1 with different input values of track degradation rates ranging from 50% to 200% of the initial data. When degradation rates increase, the tamping requirements, illustrated by *TS* in TeO, and the tamping expenditures, represented by *NPC* in EcO, increase almost in the same manner which is close to linear.

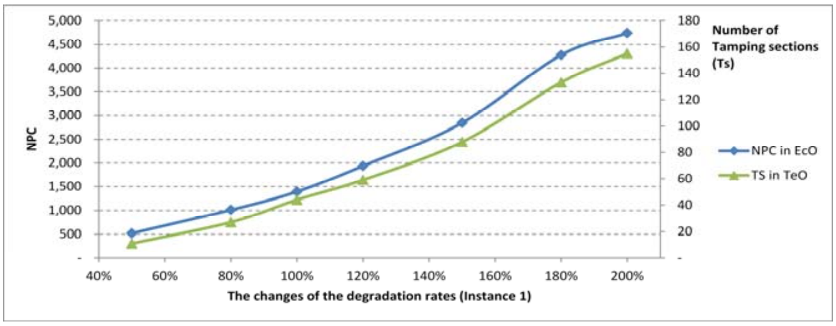


Figure 10: Sensitivities of NPC and TS as a function of degradation rate

The results obtained from the proposed models show that the tamping expenditure can be significantly decreased. It is however under the assumption of the sound prediction of track quality behaviour over time. If the tracks degradation increases due to e.g. age or increased traffic, it will lead to a linearly climbed condition-based tamping work, as presented in Figure 10. The additional tamping beyond the optimal schedule which is based on the fixed track degradations, could suddenly offset the savings presented from the proposed PDSS. It is therefore necessary to add a buffer value to the track degradation rate in practice, ensuring the full coverage of the tamping needs. Meanwhile a frequent track quality survey and continuous tamping schedule adjustment are also necessary to supplement a sound preventive tamping strategy.

7. Conclusion

This paper presented a Phase-based Decision Support System (PDSS) for scheduling railway predictive condition-based tamping maintenance aiming to reduce the total tamping cost. Three systematic optimization phases, i.e. the Technical Optimization phase (TeO), the Economic Optimization phase (EcO) and the Constrained Optimization phase (CoO), were formulated in the proposed PDSS to support railway infrastructure managers to seek the most suitable tamping schedule for a given railway track. Mixed Integer Linear Programming models were formulated in these phases. The TeO phase was used to identify the minimum tamping needs from the pure technical point of view. The EcO model was applied to find an optimal tamping schedule with the least Net Present Costs. The CoO phase was used to engage the railway experts to adjust the optimal schedule from the EcO phase via the budget constraints and the planner preferences. The usage of the PDSS was explored on a case study, including a Danish railway track between Odense and Frederica with 57.2 km of length. Compared to the existing literature, the total costs were reduced up to 40% using the proposed PDSS.

In the mathematical models of the PDSS, two geometry indicators, the standard deviation of longitudinal level defects and the standard deviation of horizontal alignment defects, were monitored simultaneously based on the condition-based principal. As a result of the Danish case study, the detection of tamping requirements were improved 6% and therefore strengthen the track quality control. Furthermore, the analysis of the results attained in the EcO model application showed that a longer period of predictive tamping planning will result in a less costly schedule than yearly planning in practice. Therefore, a phase-based mathematical programming approach such as the proposed PDSS presented in this paper, has great potential to support the preventive tamping decisions in practice.

This paper envisions improvements in two potential areas putting forward for future research. A full-scale application as concerns a meta-heuristic algorithm is helpful to be able to schedule the preventive maintenance for any large-scale track network. And through an inclusion of other track degradation formulations such as an exponential increased track degradation would be great interests of railway infrastructure managers.

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Appendix

To summarize, the mathematical model for the preventive conditional-based tamping planning is formulated by (1-23). The model is non-linear due to Constraints (5), Constraints (6) and

Constraints (9). It is necessary to linearize these constraints for the integer program IBM ILOG CPLEX to be able to solve the model.

Linearization

The nonlinear Constraints (5) can be replaced by the linear constraints (1a-4a).

$$w_i^t \le M \cdot x_i^t \qquad \forall i \in N, t \in T \tag{1a}$$

$$s_i^t - M \cdot \left(1 - x_i^t\right) - M \cdot v_i^t \le w_i^t \le s_i^t \qquad \forall i \in N, t \in T \tag{2a}$$

$$r_i^t - M \cdot \left(1 - x_i^t\right) - M \cdot (1 - v_i^t) \le w_i^t \le r_i^t \qquad \forall i \in N, t \in T \tag{3a}$$

$$M \cdot (v_i^t - 1) \le s_i^t - r_i^t \le M \cdot v_i^t \qquad \forall i \in N, t \in T \tag{4a}$$

where v_i^t is an auxiliary binary variable and M is a sufficiently large number. The nonlinear constraints (6) can be expressed by the linear constraints (5a-7a).

$$M \cdot \left(q_i^t - 1\right) \le a\left(s_i^{t-1} + d_i\right) + b \le M \cdot q_i^t \qquad \forall i \in N, t \in T, t > 0 \tag{5a}$$

$$r_i^t \le M \cdot q_i^t \qquad \forall i \in N, t \in T \tag{6a}$$

$$a\left(\sigma_i^{t-1} + d_i\right) + b - M \cdot \left(1 - q_i^t\right) \le r_i^t \le a\left(\sigma_i^{t-1} + d_i\right) + b + M \cdot \left(1 - q_i^t\right) \quad \forall i \in N, t \in T, t > 0 \tag{7a}$$

where q_i^t is an auxiliary binary variable and M is a sufficiently large number. The nonlinear constraint (9) can be reformulated by the following linear constraints (8a-9a).

$$u_i^{t-1} - M \cdot x_i^{t-1} \le u_i^t \le u_i^{t-1} + M \cdot x_i^{t-1} \qquad \forall i \in N, t \in T, t > 0 \tag{8a}$$

$$\sigma_i^{t-1} - M \cdot \left(1 - x_i^{t-1}\right) \le u_i^t \le \sigma_i^{t-1} + M \cdot \left(1 - x_i^{t-1}\right) \quad \forall i \in N, t \in T, t > 0 \tag{9a}$$

Paper 3

Optimal Scheduling of Railway Track Possessions in Large-Scale Projects with Multiple Construction-Works

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Optimal Scheduling of Railway Track Possessions in Large-Scale Projects with Multiple Construction Works

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Abstract: This paper addresses the railway track possession scheduling problem (RTPSP), where a large-scale railway infrastructure project consisting of multiple construction works is to be planned. The RTPSP is to determine when to perform the construction works and in which track possessions while satisfying different operational constraints and minimizing the total construction cost. To find an optimal solution of the RTPSP, this paper proposes an approach that, first, transfers the nominal market prices into track-possession-based real prices, and then generates a schedule of the construction works by solving a mixed-integer linear-programming model for the given track blocking proposal. The proposed approach is tested on a real-life case study from the Danish railway infrastructure manager. The results show that, in 2 h of computing time, the approach is able to provide solutions that are within 0.37% of the optimal one for six different blocking proposals and two alternative construction providers, so it can be used as an effective support tool in the primary planning stage to suggest preferable track possessions within the existing railway services. **DOI: 10.1061/(ASCE)CO.1943-7862.0001289.**

Introduction

According to European Commission (2015), railway transported 6.6% of all passengers and 11.7% of all freights in Europe in 2013. This high demand combined with limited railway infrastructures make it crucial to efficiently plan construction works in the network in order to do such things as minimize costs, train delays, passenger inconvenience, and closures of sections. Nowadays, scheduled railway services are rarely shut down because of infrastructure works, and most of the construction works are implemented at night, on weekends, or whenever railway traffic is limited (Budai-Balke 2009). As a result, infrastructure managers (IMs) face a significant decrease in productivity of the personnel involved in the construction works and higher labor and machinery costs to perform them. Therefore, it becomes of paramount importance to optimize the plan to carry out projects involving construction works.

In this paper, an optimization problem called railway track possession scheduling problem (RTPSP) is considered. A large-scale railway project consisting of multiple construction works (or tasks) is to be planned. Each task has to be implemented within the given planning horizon (usually spanning 3–4 years) in one or more track possessions (e.g., nighttime, full-day closures, weekends). The time to complete each task and the cost incurred depend on the track possessions selected. Precedence relationships between pairs of tasks and limits on the maximum number of simultaneous tasks to carry out are considered. Moreover, continuity of the operations of each task and incompatibility between tasks and time slots of the planning horizon are also taken into account. The RTPSP is to find a plan to carry out all construction works of the project while minimizing the total construction costs (TCCs) and satisfying all aforementioned operational constraints.

There are two main issues behind the RTPSP. The first issue is the planning problem itself, which is impractical to solve to optimality manually but requires a proper efficient automatic tool. The second issue concerns estimating the unit cost of the single construction works, which is not transparently available from the market (Rambøll 2012; Li et al. 2015) because it is for road works and other construction markets.

The contribution of this paper is threefold. First, a method to estimate the price of each task by applying a top-down approach that starts from nominal market prices to derive the expected price incurred when carrying out each task under each given track possession is provided. Second, a mathematical formulation based on mixed-integer linear programming (MILP) that models the goal and the different operational constraints involved in the RTPSP is introduced. Third, the proposed MILP model is validated on a real-life instance provided by the Danish National IM (Rail Net Denmark) and the effectiveness of the approach is proved by showing that an optimal plan (or a plan that is provably very close to an optimal one) can be found in reasonable amounts of computing time.

The remainder of the paper is organized as follows. First, the literature on the topic is reviewed, and the RTPSP is formally introduced. Then, the approach used to derive the cost associated with each task and each possession type is illustrated, and the proposed MILP model for the RTPSP is explained in detail. The case study provided by Rail Net Denmark is presented along with the achieved computational results. Finally, the main findings of the paper are summarized, and future research directions are outlined.

Literature Review

In the literature, there are three main streams of research related to estimating the total cost of large-scale construction projects in the primary planning phase: (1) graphic scheduling methodologies, (2) database forecasting models, and (3) mathematical modeling.

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In graphic scheduling methodologies, the plan of the project is carried out by using graphical tools first, and then the total cost and the project makespan are computed based on the output schedule. Two main methods falling in this category can be found in the literature: line of balance (LOB) (i.e., graphical techniques used in conjunction with precedence diagrams where the x-axis represents the timeline of the project and the y-axis identifies the work areas) and linear scheduling method (LSM) (i.e., more advanced LOBs combined with graphical scheduling methods focusing on continuous resource utilization in repetitive activities). Johnston (1981) gave a review of the LSM and assessed its potential usage in highway construction projects. Tang et al. (2014) applied the LSM and constraint programming techniques to solve a multiobjective optimization problem arising in railway infrastructure projects; even though fixed duration was taken into account as a constraint, and resource leveling and minimum changes to the schedule were also considered as objectives, the project overall cost and track possessions were not considered in the study. Reda (1990) and Harmelink (2001) carried out a comparison between scheduling methods and illustrated the advantages of using LSM for projects with repeating activities. Harris and Ioannou (1998) and Yamín and Harmelink (2001) gave an overview and integrated the two methods (LOB and LSM) into a so-called repetitive scheduling method (RSM). The main advantage of all the aforementioned graphic scheduling methods is to provide a practical graphic layout of the project; indeed, the planner can see which and where the tasks (y-axis) will take place at certain time point (x-axis). This provides a practical way of tracking and therefore managing the project. Nonetheless, these methods are suitable to schedule continuous repetitive activities and are mainly useful at a detailed planning level because different task details, such as task locations, are needed.

Database forecasting models tackle the problem of planning a project from a generic perspective. In particular, a project database based on the historical data is collected first, and then the most relevant attributes and weights to estimate the total cost for the future project to plan are identified. Case-based reasoning (CBR) methods were reviewed in Richter and Weber (2013) and applied, for example, in Kim (2011) and Kim and Kim (2010) to solve actual cases. A prediction model for estimating construction costs was also introduced in Wilmot and Mei (2005). Database forecasting models are usually hard to implement within railway projects because the track possessions that will be used to carry out the tasks are based, for example, on rail traffic density, track layouts (single track or double track), and infrastructure locations (on a bridge, at stations, or in tunnels), and all these elements strongly vary from project to project. Moreover, the research in database forecasting models does not consider any task scheduling problem, so no mathematical optimization model is involved.

In mathematical modeling, a large-scale project can be represented as an objective function subject to a set of constraints, where the decision variables represent the decisions to make about when and how to carry out each task of the project. The model is described with a MILP (Nemhauser and Wolsey 1988; Taha 2006; Chen et al. 2010). Mathematical modeling has been extensively studied in the literature to solve project scheduling problems (PSPs) (Demeulemeester and Herroelen 2002). The critical path method (CPM) is the most common method used to solve PSPs; the set of tasks are represented as a graphical network of nodes and arcs, and the critical activities are identified by computing the longest critical path from the start to the end of the project. The total expected cost and the project plan can then be computed by either solving the MILP model with a general-purpose MILP solver or developing an algorithm that is able to find a feasible solution as close as possible to an optimal one. The research handbook provided by Demeulemeester and Herroelen (2002) gave reviews of the CPM models. To the best of the authors' knowledge, the RTPSP addressed in this paper and in particular work possessions as defined within a railway context have not been addressed in the literature about mathematical modeling so far. The most relevant applications of the CPM to problems with features similar to the RTPSP are Yang and Chen (2000), Vanhoucke (2005), and Vanhoucke and Debels (2007), where the working (possession) patterns scheduling problem were considered by introducing time-switch constraints. Later on, Vanhoucke (2006) and Vanhoucke and Debels (2007) developed heuristic algorithms to determine a near-optimal schedule for a PSP where the goal was to finish the project with a prespecified target duration and at a minimum direct cost, but the selection of alternative track possessions (or working patterns) was not considered.

Formal Definition of the RTPSP

Let $\mathcal{I}$ be the index set of tasks to schedule in the considered construction project. Each task $i \in \mathcal{I}$ requires a certain amount of work, v_i, called volume.

All tasks must be completed within a given planning horizon, usually spanning 3–4 years. Each week is divided into 12 time slots, where Time Slots 1, 3, 5, 7, and 9 represent daytime from Monday to Friday, 2, 4, 6, 8, and 10 represent nighttime from Monday to Friday, 11 represents Saturday, and 12 represents Sunday.

Let $\mathcal{S}$ be the index set of all time slots of the planning horizon. The set $\mathcal{S}$ is partitioned into five subsets $\mathcal{S} = \mathcal{T}_1 \cup \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10} \cup \mathcal{T}_{11}$, where $\mathcal{T}_1$ is the set of daytime time slots (i.e., 1, 3, 5, 7, and 9) of each week, $\mathcal{T}_2$ the set of Monday nights (i.e., 2), $\mathcal{T}_4$ the set of Tuesday, Wednesday, and Thursday nights (i.e., 4, 6, 8), $\mathcal{T}_{10}$ the set of Friday nights (i.e., 10), and $\mathcal{T}_{11}$ the set of Saturdays and Sundays (i.e., 11 and 12). Let $\mathcal{T}$ be the set of all time slots from Monday to Friday, i.e., $\mathcal{T} = \mathcal{T}_1 \cup \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$. A day $d(t)$ and a week $w(t)$ are associated with each time slot $t \in \mathcal{S}$. A predecessor time slot π_t^1 is associated with each time slot $t \in \mathcal{T}_1$ defined as $\pi_t^1 = \max\{t' \in \mathcal{T}_1 : t' < t\}$. Similarly, a predecessor time slot π_t^2 is associated with each time slot $t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$ defined as $\pi_t^2 = \max\{t' \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10} : t' < t\}$.

Four types of track possessions are defined: interval possession (denoted as P1) between the existing running traffic in weekday daytime (i.e., in time slots of the set $\mathcal{T}_1$); night possession (P2) in weekday nights (i.e., in time slots of the sets $\mathcal{T}_2$, $\mathcal{T}_4$, and $\mathcal{T}_{10}$); weekend possession (P3) on Friday night and during the weekend (i.e., in time slots $\mathcal{T}_{10}$ and $\mathcal{T}_{11}$); and full-closure possession (P4) in one or both time slots of the same day.

Let $\mathcal{W}$ be the index set of weekends where P3 possessions can take place ($\mathcal{W} \subseteq \{w(t) : t \in \mathcal{S}\}$), and let $\mathcal{D}$ be the index set of days where P4 possessions can take place ($\mathcal{D} \subseteq \{d(t) : t \in \mathcal{S}\}$). The set $\mathcal{W}$ and $\mathcal{D}$ define the blocking proposal, that is, the weekends and days where P3 and P4 possessions are allowed. A predecessor $\pi_w^3 \in \mathcal{W}$ is associated with each weekend $w \in \mathcal{W}$ defined as $\pi_w^3 = \max\{w' \in \mathcal{W} : w' < w\}$. Similarly, a predecessor $\pi_d^4 \in \mathcal{D}$ is associated with each day $d \in \mathcal{D}$ defined as $\pi_d^4 = \max\{d' \in \mathcal{D} : d' < d\}$. The first day (week, respectively) of the set $\mathcal{D}$ ($\mathcal{W}$, respectively) does not have an associated predecessor.

The working speed (also called productivity) to carry out each task $i \in \mathcal{I}$ in possession types P1, P2, P3, and P4 are indicated with p_i^1, p_i^2, p_i^3, and p_i^4, respectively.

The set $\mathcal{P}$ contains all pairs of tasks with a precedence constraint, meaning that if $(i,j) \in \mathcal{P}$ then task $i \in \mathcal{I}$ must be completed before task $j \in \mathcal{I}$ starts ($i \prec j$). Based on the set $\mathcal{P}$, the set $\mathcal{I}^-$ of tasks that precede at least one other task and the set $\mathcal{I}^+$ of tasks that are preceded by at least one task are defined as $\mathcal{I}^- = \{i \in \mathcal{I}:(i,j) \in \mathcal{P}\}$ and $\mathcal{I}^+ = \{j \in \mathcal{I}:(i,j) \in \mathcal{P}\}$, respectively.

At most $\bar{m}$ tasks can be carried out simultaneously. Moreover, tasks can be assigned to no more than $\bar{b}^1$ ($\bar{b}^2$, respectively) time slots of the set $\mathcal{T}_1$ ($\mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$, respectively) in working possession P1 (P2, respectively), no more than $\bar{b}^3$ weekends of the set $\mathcal{W}$ in working possession P3, and no more than $\bar{b}^4$ days of the set $\mathcal{D}$ in working possession P4.

A cost for carrying out each task $i \in \mathcal{I}$ in track possession type P1, P2, P3, and P4 is indicated by c_i^1, c_i^2, c_i^3, and c_i^4, respectively. A detailed description of how such costs are computed is given in the next section.

Estimating the Price of Each Task in Each Track Possession

The prices for railway construction works are not transparently available from the market because they depend on the working times and the durations (i.e., the track possession) to carry out each task, and the real price corresponding to the track possession can only be offered in the construction bidding (tendering) from case to case. Unfortunately, these prices are already needed in the primary planning phase while deciding the track possession to perform the tasks and the track blocking plan for the existing scheduled trains.

The available market prices for similar projects in the construction market are called nominal prices and are based on standard working hours. Previous studies (Cantarelli et al. 2012; Li et al. 2015) proved that there is a high risk of budget overruns if such nominal prices are used to estimate the cost of a construction-based project.

To solve this challenge, Li et al. (2015) provided a method for transferring the nominal market prices into real prices for track possessions. They suggested separating the nominal market price into three subcategories of prices for materials, labors, and machineries. In particular, the real track-possession price is calculated by fixing the cost for materials, and then recomputing the labor and machinery costs based on the track possession. The labor costs were obtained by comparing the paying hours with the effective working hours for each track possession; this implies that possible reasons that may slow down the productivity have to be kept into account. For example, in night possession 7.5 h are paid as 15 standard hours (the labor wage at night is doubled) but only 5 of those 7.5 h are effective working hours because of safety settings, coffee breaks, and construction preparations; this implies that night possession labor cost can be in practice three times higher than the nominal price. A limit of the bottom-up approach proposed by Li et al. (2015) is that real construction-work costs are estimated based on the effective working hours only, but without linking them to the working productivity in each track possession. As a matter of fact, the actual working hours (determining the real costs) are strongly correlated to the productivity (e.g., less effective working hours surely turn into a lower productivity). To overcome this issue, a new top-down approach that links these two factors is introduced.

The approach proposed in this paper to compute the costs c_i^1, c_i^2, c_i^3, and c_i^4 to carry out each task $i \in \mathcal{I}$ in the different time slots $t \in \mathcal{T}_1$, in the time slots $t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$, on the weekends $w \in \mathcal{W}$, and on the days $d \in \mathcal{D}$, respectively, uses the same three subcategories suggested in Li et al. (2015), but, instead of using a bottom-up approach starting from the possible detailed losses of time that can occur under each track possession, it uses a top-down approach based on working productivities per track possession; cost ratios for labor, material, and machinery; and labor wage factor per track possession. The approach works as follows.

For each task $i \in \mathcal{I}$, the three subcategories of costs (i.e., material, machinery, and labor) are computed for each unit of work (e.g., meters) as follows:

Unit material cost:

$$\mathrm{Mat}C_i = \bar{c}_i \cdot R_i^{\mathrm{Mat}} \tag{1}$$

Unit machinery cost:

$$\mathrm{Mac}C_i^\beta = \bar{c}_i \cdot R_i^{\mathrm{Mac}} \cdot \frac{\bar{p}_i}{p_i^\beta} \quad \beta \in \{1,2,3,4\} \tag{2}$$

Unit labor cost:

$$\mathrm{Lab}C_i^\beta = \bar{c}_i \cdot R_i^{\mathrm{Lab}} \cdot \frac{\bar{p}_i}{p_i^\beta} \cdot f^\beta \quad \beta \in \{1,2,3,4\} \tag{3}$$

where $\bar{c}_i$ = unit cost of the nominal price for task $i \in \mathcal{I}$; R_i^{Mat}, R_i^{Mac}, and R_i^{Lab} = three cost percentage ratios for material, machineries, and labor required for task $i \in \mathcal{I}$ such that $R_i^{\mathrm{Mat}} + R_i^{\mathrm{Mac}} + R_i^{\mathrm{Lab}} = 1$, and $R_i^{\mathrm{Mat}}, R_i^{\mathrm{Mac}}, R_i^{\mathrm{Lab}} \geq 0$; $\bar{p}_i$ = productivity of normal working hours of task $i \in \mathcal{I}$; p_i^β = productivity factor to carry out task $i \in \mathcal{I}$ in possession type $\beta \in \{1,2,3,4\}$ (as defined in the previous section); and f^β = labor wage factor for possession type $\beta \in \{1,2,3,4\}$.

Eq. (1) computes the unit material cost $\mathrm{Mat}C_i$ by using the nominal unit price $\bar{c}_i$ and material ratio R_i^{Mat} for each task $i \in \mathcal{I}$; therefore, $\mathrm{Mat}C_i$ does not depend on the specific track possession. Eq. (2) computes the unit machinery cost $\mathrm{Mac}C_i^\beta$ for each task $i \in \mathcal{I}$ in each track possession $\beta \in \{1,2,3,4\}$; because $\mathrm{Mac}C_i^\beta$ is inversely proportional to the working productivity p_i^β in track possession β for task i, a higher productivity (compared with productivity in normal working hours $\bar{p}_i$) results in shorter execution times [represented by $\bar{p}_i/p_i^\beta$ in Eq. (2)] and ultimately leads to cheaper unit machinery costs $\mathrm{Mac}C_i^\beta$. Eq. (3) computes the unit labor cost $\mathrm{Lab}C_i^\beta$ for each task $i \in \mathcal{I}$ in each track possession $\beta \in \{1,2,3,4\}$; labor costs are computed similarly to machinery costs, but by taking into account an additional labor wage factor f^β that is directly proportional to the labor costs themselves. Finally, the total unit price c_i^β to perform each task $i \in \mathcal{I}$ in track possession $\beta \in \{1,2,3,4\}$ is computed as the sum of the aforementioned material, machinery, and labor unit costs, namely

$$\begin{aligned} c_i^\beta &= [(1)+(2)+(3)]p_i^\beta = (\mathrm{Mat}C_i + \mathrm{Mac}C_i^\beta + \mathrm{Lab}C_i^\beta)p_i^\beta \\ &= \bar{c}_i[R_i^{\mathrm{Mat}} p_i^\beta + \bar{p}_i(R_i^{\mathrm{Mat}} + R_i^{\mathrm{Lab}} f^\beta)] \quad i \in \mathcal{I} \quad \beta \in \{1,2,3,4\} \end{aligned} \tag{4}$$

Proposed MILP Formulation for the RTPSP

The MILP formulation proposed for the RTPSP makes use of 14 sets of variables (four sets of decision variables and 10 sets of auxiliary variables).

The decision variables are represented by following four sets:

- $x_{it}^1 \in \{0,1\}$: binary variable equal to 1 if the task $i \in \mathcal{I}$ is performed in the time slot $t \in \mathcal{T}_1$ in the track possession type P1 (0 otherwise);
- $x_{it}^2 \in \{0,1\}$: binary variable equal to 1 if the task $i \in \mathcal{I}$ is performed in the time slot $t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$ in the track possession type P2 (0 otherwise);

- $x_{iw}^3 \in \{0,1\}$: binary variable equal to 1 if the task $i \in \mathcal{I}$ is performed in the P3 possession type on the weekend $w \in \mathcal{W}$ (0 otherwise); and
- $x_{id}^4 \in \{0,1\}$: binary variable equal to 1 if the task $i \in \mathcal{I}$ is performed in the P4 possession type on the day $d \in \mathcal{D}$ (0 otherwise).

The following 10 sets of auxiliary variables are also used:

1. Binary variables to indicate if at least one task is performed in a time slot, day or weekend:
   - $y_t^1 \in \{0,1\}$: equal to 1 if at least one task is performed in the possession type P1 in the time slot $t \in \mathcal{T}_1$;
   - $y_t^2 \in \{0,1\}$: equal to 1 if at least one task is performed in the possession type P2 in the time slot $t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$;
   - $y_w^3 \in \{0,1\}$: equal to 1 if at least one task is performed in the possession type P3 on the weekend $w \in \mathcal{W}$; and
   - $y_d^4 \in \{0,1\}$: equal to 1 if at least one task is performed in the possession type P4 on the day $d \in \mathcal{D}$.
2. Real variables to model precedence constraints:
   - $s_i \in \mathbb{R}_+$: time slot when task $i \in \mathcal{I}$ starts; and
   - $e_i \in \mathbb{R}_+$: time slot when task $i \in \mathcal{I}$ ends.
3. Binary variables to model the continuity of possession for each task and each possession type:
   - $z_{it}^1 \in \{0,1\}$: equal to 1 if the task $i \in \mathcal{I}$ is executed for the first time in the time slot $t \in \mathcal{T}_1$ in the possession type P1;
   - $z_{it}^2 \in \{0,1\}$: equal to 1 if the task $i \in \mathcal{I}$ is executed for the first time in the time slot $t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$ in the possession type P2;
   - $z_{iw}^3 \in \{0,1\}$: equal to 1 if the task $i \in \mathcal{I}$ is executed for the first time on the weekend $w \in \mathcal{W}$ in the possession type P3; and
   - $z_{id}^4 \in \{0,1\}$: equal to 1 if the task $i \in \mathcal{I}$ is executed for the first time on the day $d \in \mathcal{D}$ in the possession type P4.

The proposed MILP formulation of the RTPSP reads as follows:

$$\min \sum_{i\in\mathcal{I}} \left(\sum_{t\in\mathcal{T}_1} r_t^1 c_i^1 x_{it}^1 + \sum_{t\in\mathcal{T}_2\cup\mathcal{T}_4\cup\mathcal{T}_{10}} r_t^2 c_i^2 x_{it}^2 + \sum_{w\in\mathcal{W}} r_w^3 c_i^3 x_{iw}^3 + \sum_{d\in\mathcal{D}} r_d^4 c_i^4 x_{id}^4 \right) \tag{5}$$

$$\text{subject to} \sum_{t\in\mathcal{T}_1} p_i^1 x_{it}^1 + \sum_{t\in\mathcal{T}_2\cup\mathcal{T}_4\cup\mathcal{T}_{10}} p_i^2 x_{it}^2 + \sum_{w\in\mathcal{W}} p_i^3 x_{iw}^3 + \sum_{d\in\mathcal{D}} p_i^4 x_{id}^4 \geq v_i \quad i \in \mathcal{I} \tag{6}$$

$$\sum_{i\in\mathcal{I}} (x_{it}^1 + x_{i,d(t)}^4) \leq \bar{m} \quad t \in \mathcal{T}_1 \tag{7}$$

$$\sum_{i\in\mathcal{I}} (x_{it}^2 + x_{i,d(t)}^4) \leq \bar{m} \quad t \in \mathcal{T}_2 \cup \mathcal{T}_4 \tag{8}$$

$$\sum_{i\in\mathcal{I}} (x_{it}^2 + x_{i,w(t)}^3 + x_{i,d(t)}^4) \leq \bar{m} \quad t \in \mathcal{T}_{10} \tag{9}$$

$$\sum_{i\in\mathcal{I}} (x_{w(t)}^3 + x_{d(t)}^4) \leq \bar{m} \quad t \in \mathcal{T}_{11} \tag{10}$$

$$x_{it}^1 \leq y_t^1 \quad i \in \mathcal{I} \quad t \in \mathcal{T}_1 \tag{11}$$

$$x_{it}^2 \leq y_t^2 \quad i \in \mathcal{I} \quad t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10} \tag{12}$$

$$x_{iw}^3 \leq y_w^3 \quad i \in \mathcal{I} \quad w \in \mathcal{W} \tag{13}$$

$$x_{id}^4 \leq y_d^4 \quad i \in \mathcal{I} \quad d \in \mathcal{D} \tag{14}$$

$$\sum_{t\in\mathcal{T}_1} y_t^1 \leq \bar{b}^1 \tag{15}$$

$$\sum_{t\in\mathcal{T}_2\cup\mathcal{T}_4\cup\mathcal{T}_{10}} y_t^2 \leq \bar{b}^2 \tag{16}$$

$$\sum_{w\in\mathcal{W}} y_w^3 \leq \bar{b}^3 \tag{17}$$

$$\sum_{d\in\mathcal{D}} y_d^4 \leq \bar{b}^4 \tag{18}$$

$$y_t^1 + y_{d(t)}^4 \leq 1 \quad t \in \mathcal{T}_1 \tag{19}$$

$$y_t^2 + y_{d(t)}^4 \leq 1 \quad t \in \mathcal{T}_2 \cup \mathcal{T}_4 \tag{20}$$

$$y_t^2 + y_{w(t)}^3 + y_{d(t)}^4 \leq 1 \quad t \in \mathcal{T}_{10} \tag{21}$$

$$y_{w(t)}^3 + y_{d(t)}^4 \leq 1 \quad t \in \mathcal{T}_{11} \tag{22}$$

$$s_i \leq t[M - (M-1)(x_{it}^1 + x_{i,d(t)}^4)] \quad t \in \mathcal{T}_1 \quad i \in \mathcal{I}^+ \tag{23}$$

$$s_i \leq t[M - (M-1)(x_{it}^2 + x_{i,d(t)}^4)] \quad t \in \mathcal{T}_2 \cup \mathcal{T}_4 \quad i \in \mathcal{I}^+ \tag{24}$$

$$s_i \leq t[M - (M-1)(x_{it}^2 + x_{i,w(t)}^3 + x_{i,d(t)}^4)] \quad t \in \mathcal{T}_{10} \quad i \in \mathcal{I}^+ \tag{25}$$

$$s_i \leq t[M - (M-1)(x_{i,w(t)}^3 + x_{i,d(t)}^4)] \quad t \in \mathcal{T}_{11} \quad i \in \mathcal{I}^+ \tag{26}$$

$$e_i \geq t(x_{it}^1 + x_{i,d(t)}^4) \quad t \in \mathcal{T}_1 \quad i \in \mathcal{I}^- \tag{27}$$

$$e_i \geq t(x_{it}^2 + x_{i,d(t)}^4) \quad t \in \mathcal{T}_2 \cup \mathcal{T}_4 \quad i \in \mathcal{I}^- \tag{28}$$

$$e_i \geq t(x_{it}^2 + x_{i,w(t)}^3 + x_{i,d(t)}^4) \quad t \in \mathcal{T}_{10} \quad i \in \mathcal{I}^- \tag{29}$$

$$e_i \geq t(x_{i,w(t)}^3 + x_{i,d(t)}^4)] \quad t \in \mathcal{T}_{11} \quad i \in \mathcal{I}^- \tag{30}$$

$$e_i + 1 \leq s_j \quad (i,j) \in \mathcal{P} \tag{31}$$

$$x_{iw}^3 - x_{i,\pi_w^3}^3 \leq z_{iw}^3 \quad i \in \mathcal{I} \quad w \in \mathcal{W} \tag{32}$$

$$\sum_{w\in\mathcal{W}} z_{iw}^3 \leq 1 \quad i \in \mathcal{I} \tag{33}$$

$$x_{id}^4 - x_{i,\pi_d^4}^4 \leq z_{id}^4 \quad i \in \mathcal{I} \quad d \in \mathcal{D} \tag{34}$$

$$\sum_{d\in\mathcal{D}} z_{id}^4 \leq 1 \quad i \in \mathcal{I} \tag{35}$$

$$x_{it}^1 - x_{i,\pi_t^1}^1 \leq z_{it}^1 \quad i \in \mathcal{I} \quad t \in \mathcal{T}_1 \tag{36}$$

$$x_{it}^2 - x_{i,\pi_t^2}^2 \leq z_{it}^2 \quad i \in \mathcal{I} \quad t \in \mathcal{T}_4 \cup \mathcal{T}_{10} \tag{37}$$

$$x_{it}^2 - x_{i,\pi^2_{\pi_t^2}}^2 + x_{i,w(\pi_t^2)}^3 \leq z_{it}^2 + 1 \quad i \in \mathcal{I} \quad t \in \mathcal{T}_2 \tag{38}$$

$$x_{it}^2 - x_{i,\pi_t^2}^2 - x_{i,w(\pi_t^2)}^3 \leq z_{it}^2 \quad i \in \mathcal{I} \quad t \in \mathcal{T}_2 \tag{39}$$

$$\sum_{t \in \mathcal{T}_1} z_{it}^1 \leq 1 \quad i \in \mathcal{I} \tag{40}$$

$$\sum_{t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}} z_{it}^2 \leq 1 \quad i \in \mathcal{I} \tag{41}$$

$$x_{it}^1, y_{it}^1, z_{it}^1 \in \{0,1\} \quad i \in \mathcal{I} \quad t \in \mathcal{T}_1 \tag{42}$$

$$x_{it}^2, y_{it}^2, z_{it}^2 \in \{0,1\} \quad i \in \mathcal{I} \quad t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10} \tag{43}$$

$$x_{iw}^3, y_{iw}^3, z_{iw}^3 \in \{0,1\} \quad i \in \mathcal{I} \quad w \in \mathcal{W} \tag{44}$$

$$x_{id}^4, y_{id}^4, z_{id}^4 \in \{0,1\} \quad i \in \mathcal{I} \quad d \in \mathcal{D} \tag{45}$$

$$s_i, e_i \in \mathbb{R}_+ \quad i \in \mathcal{I} \tag{46}$$

The objective function Eq. (5) aims to minimize the total cost for carrying out the tasks, defined as the sum of the costs for performing them in weekday time slots in the P1 or P2 possession, on the weekends in the P3 possession, and on full days in the P4 possession. Coefficients r_t^1 are applied to fulfill the planning requirement of scheduling tasks as early as possible in order to reduced delay risks; this means that $r_{\pi_t}^1 < r_t^1$ for each $t \in \mathcal{T}_1$. Coefficients r_t^2, r_w^3, and r_d^4, play a similar role.

The constraints in Eq. (6) relate the productivity of the selected time slots, days, and weekends to carry out each task $i \in \mathcal{I}$ with its volume v_i and ensure that each task is completed in the given planning horizon.

The constraints in Eqs. (7)–(10) guarantee that no more than $\bar{m}$ tasks are implemented simultaneously in any time slot, namely, the constraints in Eq. (7) refer to time slots $\mathcal{T}_1$, constraints in Eq. (8) to time slots $\mathcal{T}_2 \cup \mathcal{T}_4$, constraints in Eq. (9) to time slots $\mathcal{T}_{10}$, and constraints in Eq. (10) to time slots $\mathcal{T}_{11}$.

The constraints in Eqs. (11)–(14) link the x and y variables. In particular, the constraints in Eq. (11) [constraints in Eq. (12)] ensure that if at least one task is carried out in time slot $t \in \mathcal{T}_1$ ($t \in \mathcal{T}_2 \cup \mathcal{T}_4 \cup \mathcal{T}_{10}$), then y_t^1 (y_t^2) is equal to 1; the constraints in Eq. (13) set y_w^3 equal to 1 if at least one task is performed on weekend $w \in \mathcal{W}$; and the constraints in Eq. (14) guarantee that if at least one task is implemented in the P4 possession on day $d \in \mathcal{D}$, then y_d^4 is equal to 1.

The constraints in Eqs. (15)–(18) model the maximum number of scheduled working periods for each possession type P1, P2, P3, and P4, respectively.

The constraints in Eqs. (19)–(22) ensure that at most one possession type is selected in each time slot.

Precedence constraints among tasks are modeled through the constraints in Eqs. (23)–(31) by determining the first and the last time slot when each task is carried out and comparing the final time slot of a given task i with the initial time slot of a given task j whenever task i must precede task j. In particular, the constraints in Eqs. (23)–(26) impose on each s_i variable not to exceed the time corresponding to any of the time slots when task $i \in \mathcal{I}^+$ is carried out; this ensures that variable s_i will correspond to the first time slot when task i is carried out. Similarly, the constraints in Eqs. (27)–(30) set variable e_i (i.e., the end time) of each task $i \in \mathcal{I}^-$ not lower than the time corresponding to any of the time slots when task i is carried out; this guarantees that e_i will correspond to the last time slot when task i is carried out. The precedence constraints between pairs of tasks (i,j) of the set $\mathcal{P}$ are then stipulated with the constraints in Eq. (31) by stating that the final time slot of task i (i.e., variable e_i) be less than the initial time slot of task j (i.e., variable s_j).

The constraints in Eqs. (32)–(33) ensure that each task $i \in \mathcal{I}$ is not interrupted before its completion with regards to the possession type P3. Indeed, the constraints in Eq. (32) guarantee that z_{iw}^3 equals 1 whenever task i is performed in the possession type P3 on the weekend $w \in \mathcal{W}$ (i.e., $x_{iw}^3 = 1$) but is not performed in the possession type P3 in the predecessor weekend of w (i.e., $x_{i,\pi_w^3}^3 = 0$). Yet the constraints in Eq. (33) stipulate that no more than one z_{iw}^3 variable can be equal to 1 for each task $i \in \mathcal{I}$, thus ensuring that task i cannot start more than once in the possession type P3. In other words, this ensures that each task is carried out on consecutive weekends until it is completed.

The constraints in Eqs. (34)–(35) stipulate that each task $i \in \mathcal{I}$ is not interrupted in the possession type P4 and work in the same vein as the constraints in Eqs. (32)–(33) for the possession type P3.

The constraints in Eqs. (36)–(41) guarantee the continuity of each task $i \in \mathcal{I}$ in the possession types P1 and P2. The constraints in Eqs. (36)–(37) set the initial time slot when the task i is carried out and are similar to the constraints in Eqs. (32) and (34) for the possession types P3 and P4. The constraints in Eqs. (40) and (41) state that each task cannot be interrupted in the possession type P1 and P2, respectively, and are the counterpart of the constraints in Eqs. (33) and (35) for the possession types P3 and P4. The constraints in Eqs. (38) and (39) set a variable z_{it}^2 equal to 1 for a given task $i \in \mathcal{I}$ and a time slot $t \in \mathcal{T}_2$ (i.e., corresponding to a Monday night possession) if and only if $x_{it}^2 = 1$ and either (*a*) $x_{i,\pi^2_{\pi_t^2}}^2 = 0$ and $x_{i,w(\pi_t^2)}^3 = 1$ (meaning that task i was not carried out on the previous Thursday night under the possession type P2, but was carried out on the previous weekend under the possession type P3), or (*b*) $x_{i,\pi_t^2}^2 = 0$ and $x_{i,w(\pi_t^2)}^3 = 0$ (meaning that task i was not carried out on the previous Friday night under either the possession types P2 or P3). Therefore, the constraints in Eqs. (36)–(41) ensure that each task is carried out on consecutive weekday nights but interruptions for weekend possessions P3 are allowed.

Finally, the constraints in Eqs. (42)–(46) define the range of the variables.

Case Study

The proposed methodology was tested on real-life data provided by Rambø ll Denmark (a railway infrastructure consultancy company) and by Rail Net Denmark (*Banedanmark*, the national railway IM in Denmark). This section provides a background of the considered case study, an overview of the construction tasks involved, a description of the possession types, an overview of the price and productivity for each track possession type, and a summary of the different scenarios and two potential construction suppliers.

Project Background

Fehmarn Belt (*Femern Bælt*) is a strait connecting the Bay of Kiel and the Bay of Mecklenburg in the western part of the Baltic Sea between the German island of Fehmarn and the Danish island of Lolland. In 2007, the Danish and German governments agreed to build a fixed link to replace the existing ferry route across the Fehmarn Belt with the aim of saving 1 h on crossing the strait and increasing crossing capacity.

The Fehmarn Belt project at the Danish side, illustrated in Fig. 1, includes both the fixed link (a new tunnel) between Rødby, Denmark, and Puttgarden, Germany, and the corresponding onshore facilities upgrading both roads and railways. The railway construction work between Ringsted and Rødby (Rg-Rb) in Denmark includes four main activities, namely, electrifying the Rg-Rb line, constructing 55 km of new track to upgrade the entire Rg-Rb corridor to double-track layout, upgrading the existing tracks for the speed of 200 km/h, and building and rebuilding the bridges along the railways (Banedanmark 2012).

The Fehmarn Belt project is divided into two sections (north and south) separated by the bridge crossing Storstrømmen. The north section with an existing double-track line between Ringsted, Denmark, and Vordingborg, Denmark, operates two passenger trains per hour per direction and is expected to increase to three passenger trains during the project time (2014–2021); due to high traveling demands of both international and local passengers, it was decided to maintain the existing traffic on a single track while construction works take place on the other track. The south section connects Vordingborg and Rødby (Vb-Rb corridor) in Denmark with a single track; the local passenger demand in the south section is lower than in the north section.

Construction Tasks

Figs. 2(a and b) show the track structure layouts of the railway cross section (the south section) before and after the Fehmarn Belt project. A new track along with a new catenary system and a new signaling system (ERTMS) are going to be constructed beside the existing track [represented by the left track of Fig. 2(b)]. The dashed frame includes the constrained construction zone (CC-Zone) where the railway traffic running on the existing track will be interrupted by the construction works, and therefore track possessions need to be considered. The construction works outside the CC-Zone can be implemented in normal working hours instead of taking track possessions.

The construction tasks located in the CC-Zone for the south section are shown in Table 1. For each task, the task identifier, a description, the volume, the unit of volume, and the working sequence are reported. The working sequences indicate precedences among tasks: tasks with Working Sequence 1 (2) must be completed before tasks with Working Sequence 2 (3) start. Tasks with the same working sequence can, in theory, be implemented simultaneously as long as no more than three tasks are scheduled simultaneously (i.e., $\bar{m} = 3$)—this is mainly because the vehicles for supplying the new materials and disposing of wastes are relying on the existing single railway track for transportation.

Track Possession Types

Four possible track possession types for the south section of the Fehmarn Belt project are defined: interval possession (P1), in the intervals of running trains, 1 day = 7.5 h from 8 a.m. to 3 p.m., Monday to Friday; night possession (P2), 1 night = 7.5 h from 10 p.m. to 5:30 a.m., Monday to Friday; weekend possession (P3), 1 weekend = 56 h from Friday 10 p.m. to Monday 6 a.m.; and gull-closure possession (P4), 1 day = 24 h any day from June to November.

Table 2 indicates the number of working weekly hours for weekday daytime and night and weekend daytime and night for each possession type. The last two rows of the table indicate the resulting paying hours for machinery and paying hours per week for labor based on the wage factors of the different pricing categories.

Price and Productivity per Track Possession Type

Table 3 reports the input data for the proposed model. The first column indicates the task identifier. The following block of three columns indicates the cost percentage ratios for materials, machineries, and labors (as introduced in §4). The next four columns report the productivity for each task under each track possession type (see §3); a dash indicates that it is not feasible to perform a task in the given possession type. The five "Unit price" columns indicate the nominal unit price along with the real prices to carry out each task in each track possession type; all prices are expressed in Danish kroner (DKK). The last column shows the unit on which the unit prices are based. The cost ratios, productivities, and nominal prices, as input data for the MILP model, were estimated by construction experts in Rambø ll Denmark based on historical data.

Table 3 shows that, for each task $i \in \mathcal{I}$, the nominal unit price ($\bar{c}_i$) is always the cheapest price, followed by the full-closure price (c_i^4) and the weekend possession price (c_i^3), that is, $\bar{c}_i < c_i^4 < c_i^3$. Then, both c_i^1 and c_i^2 are always greater than c_i^3, but no dominance exists between them, i.e., $c_i^1 \gtrless c_i^2$; this is caused by the combination of low working productivity and extra labor cost out of the standard working hours.

Track Closure Proposals and Potential Suppliers

The Fehmarn Belt project is being carried out between 2014 and 2021. The first 4 years (2014–2017) were planned for building and rebuilding bridges; only a few weekends are needed because the bridges are mainly constructed out of the CC-Zone, so this period is out of scope for this study. On the contrary, only years

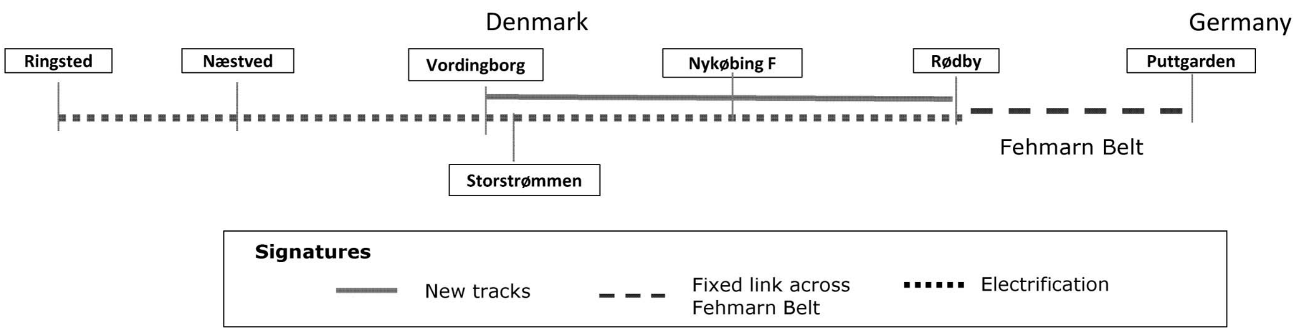


Fig. 1. Fehmarn Belt project overview

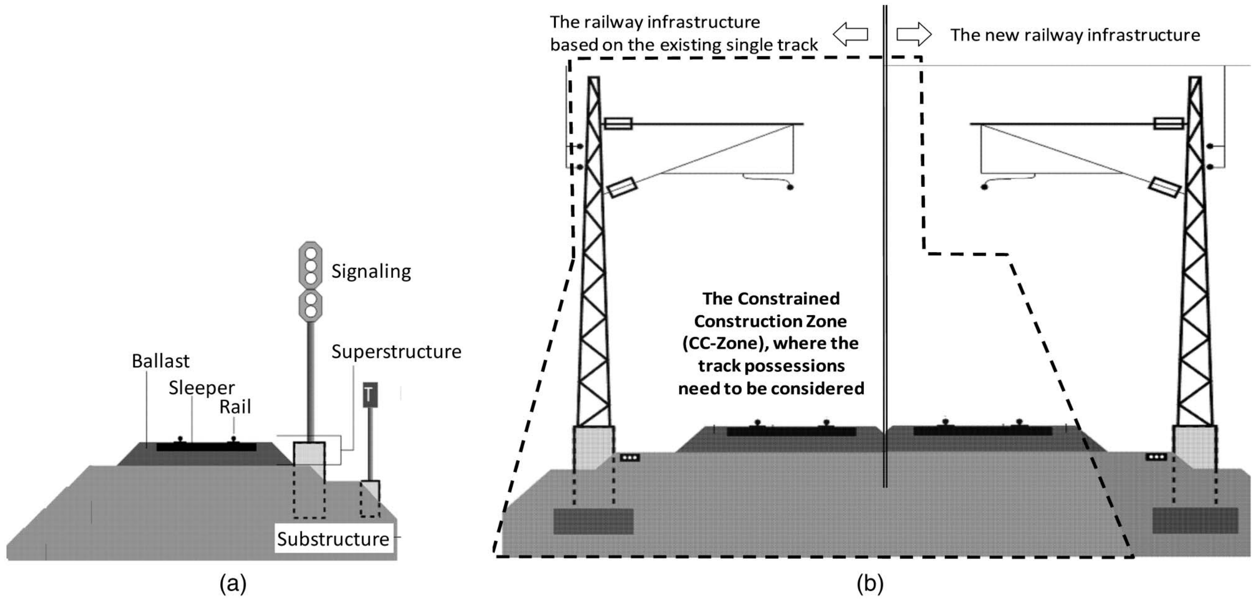


Fig. 2. Comparison of railway structures before and after the Fehmarn Belt project: (a) existing single-track layout; (b) future double-track layout

Table 1. List of Tasks in the CC-Zone for the South Section

Task identifier	Task description	Volume	Working sequence
W1	Earthwork	12,570 m	1
W2	Dam extensions	24,000 m	1
W3	Track works	7,320 m	2
W4	Catenary works	3,582	3
W5	Connecting to new track	14	2
W6	Crossing pipes for wild animals	5	1
W7	Turnout (S&C)	16	2
W8	Replacement of existing rails	45,000 m	2
W9	New subballast in the existing track	5,900 m	1
W10	Retaining walls, among others	800 m	1

Table 2. Paying Hours per Track Possession Type per Week

		Possession type			
Pricing category	Wage factor	P1	P2	P3	P4
Weekday daytime	100%	37.5	—		80
Weekday night	200%	—	37.5	24	40
Weekend daytime	150%	—	—	32	32
Weekend night	200%	—	—	—	16
Sum	—	37.5	37.5	56	168
Paying standard	Machine	37.5	37.5	56	168
Hours per week	Labor	37.5	75	96	240

2018–2021 are considered. The Danish government and Rail Net Denmark agreed on three possible full closure proposals, referred to as S1, S2, and S3 in the following. Therefore, this study considers the following six scenarios (two for each full closure proposal):

- **S1**: 6 months of full closure planned in 2020; the other three track possessions can be (but do not necessarily have to be) used in the remaining planning period;
- **S1'**: same as S1, but weekend possessions can be used at most once per month;
- **S2**: 10 months of full closure are planned overall (3 in 2019, 4 in 2020, 3 in 2021); the other three track possessions can be (but do not necessarily have to be) used in the remaining planning period;
- **S2'**: same as S2, but weekend possessions can be used at most once per month;
- **S3**: 13 months of full closure are planned overall (3 in 2018, 3 in 2019, 4 in 2020, 3 in 2021); the other three track possessions can be (but do not necessarily have to be) used in the remaining planning period;
- **S3'**: same as S3, but weekend possessions can be used at most once per month;

The total project cost was calculated for two candidate construction suppliers, i.e., the standard European supplier and a supplier with a lower labor cost. The labor cost for the standard European supplier comes from expert estimation and is presented in Table 3. The other supplier has a labor cost that is 35% cheaper than the standard one, while the other features remain the same.

Table 4 shows the full closure weeks (i.e., weeks defining the set $\mathcal{D}$ where P4 possessions are allowed) and the maximum number of track possessions per type (i.e., $\bar{b}_1$, $\bar{b}_2$, $\bar{b}_3$, $\bar{b}_4$) for each scenario. Weeks are numbered starting from Week 1 on January 1, 2018 until Week 209 ending on January 1, 2022.

Computational Results and Discussions

The proposed MILP model was solved with the general-purpose MILP solver *CPLEX version 12.6.0.0*. Table 5 gives the results achieved on the six scenarios for both suppliers.

Table 5 reports, for each scenario and each supplier, the TCC, the optimal number of possessions (i.e., the distribution of track possessions) for each type (P1, P2, P3, P4), and the total computing time of the *CPLEX* solver in the format hours:minutes:seconds. For the standard supplier, the "Gap" column indicates the percentage gap with respect to the cost of the best solution found in Scenario S3. For the lower labor cost supplier, the "Saving" column indicates the percentage saving with respect to the cost of the corresponding scenario carried out by the standard supplier. When the computing time is 2 h, the reported solution may not be the optimal one. The

Table 3. Prices and Working Productivity per Track Possession Type

Task identifier	Cost ratio			Productivity				Unit price (DKK)					
i	R_i^{Mat} (%)	R_i^{Mac} (%)	R_i^{Lab} (%)	p_i^1	p_i^2	p_i^3	p_i^4	$\bar{c}_i$	c_i^1	c_i^2	c_i^3	c_i^4	Unit
W1	10	49	41	5.5	6	80	37	5,408	13,815	18,286	9,586	8,095	Meters
W2	5	51	44	8	12.5	125	56	8,000	20,350	19,020	13,055	11,311	Meters
W3	66	21	13	—	110	1,000	450	2,976	—	3,910	3,436	3,245	Meters
W4	71	20	9	—	6	50	22	80,958	—	100,718	92,171	87,995	—
W5	0	65	35	—	—	1.0	0.45	2,000,000	—	—	3,080,000	2,698,667	—
W6	40	38	22	—	—	1.0	0.45	3,000,000	—	—	4,004,926	3,647,616	—
W7	68	22	10	—	—	1.0	0.45	1,888,249	—	—	2,189,415	2,084,973	—
W8	93	5	2	—	500	4,500	2,000	1,980	—	2,091	2,035	2,016	Meters
W9	46	35	19	—	—	200	90	5,500	—	—	7,109	6,540	Meters
W10	45	36	19	10	15	130	58	30,000	46,500	42,985	37,060	34,362	Meters

Table 4. Full Closure Weeks and Maximum Number of Work Possessions per Type

(lr)2-5 (lr)6-9	Full closure weeks (P4)				Maximum work possessions			
scenario	2018	2019	2020	2021	$\bar{b}^1$	$\bar{b}^2$	$\bar{b}^3$	$\bar{b}^4$
S1	—	—	127–152	—	915	915	183	182
S1’	—	—	127–152	—	915	915	42	182
S2	—	75–87	127–144	179–191	825	825	165	308
S2’	—	75–87	127–144	179–191	825	825	38	308
S3	21–35	75–87	127–144	179–191	760	760	152	399
S3’	21–35	75–87	127–144	179–191	760	760	35	399

“Nominal” row indicates the total nominal construction costs without taking track possessions into account.

Fig. 3 reports the track possession schedule obtained from the proposed MILP model for Scenario S2’.

Cost Comparison

The results in Table 5 show that the total construction cost was in the range between 1.1 and 1.22 billion DKK when performed by the standard supplier; this means that the total expected cost is at least 28% higher than the total nominal construction cost, so using nominal prices implies a high risk of experiencing budget overruns. Fig. 4 depicts these overall cost comparisons among all scenarios. For each scenario, two bars are reported: the one on the left indicates the total construction cost with the standard supplier and the one on the right with the supplier with cheaper labor cost. The percentage on top of the right bars shows the cost savings with respect to the standard supplier, and the line indicates the total full-closure duration in each scenario. In Scenarios S1, S2, S2’, and S3’ for both suppliers, the optimal solution was found in, at most, 79 min of computing time; moreover, for Scenario S3, the final solution was provided in 2 h of computing time and is provably within 0.37% from optimality for the standard supplier and within 0.33% for the one with a cheaper price. From the results in Table 5 and Fig. 4, it can be seen that choosing the supplier with lower labor cost would turn into 3.2–3.8% overall cost savings.

In general, the total project cost decreases when the days of full-closure possession increase. Indeed, Scenarios S1 and S2 resulted in a higher TCC by 4.9% (53 million DKK) and by 1.9% (21 million DKK), respectively, with respect to Scenario S3. Moreover, adding the constraint that there can be at most one weekend possession per month (i.e., moving from Scenarios S1, S2, S3 to S1’, S2’, S3’), Scenario S1’ is no longer feasible, Scenario S2’ costs 11.2% (124 million DKK) more than S3, and Scenario S3’ costs 4.8% (52 million DKK) more than S3; this happens because expensive night possessions and interval possessions have to be taken instead of weekend possessions. By comparing Scenario S3’ and Scenario S2’, it can be seen that the total saving of construction cost that can be achieved is approximately 71 million DKK; this suggests that increasing full closures by 3 months can result into a reduction of the total cost, the number of P1 possessions by more than 1 year (451 days), and the number of P2 possessions by half a year (171 nights).

However, to make the final decision, the passenger loss caused by the additional track closures need to be estimated and added on top of the direct construction cost to seek the most economical solution overall (Li et al. 2013).

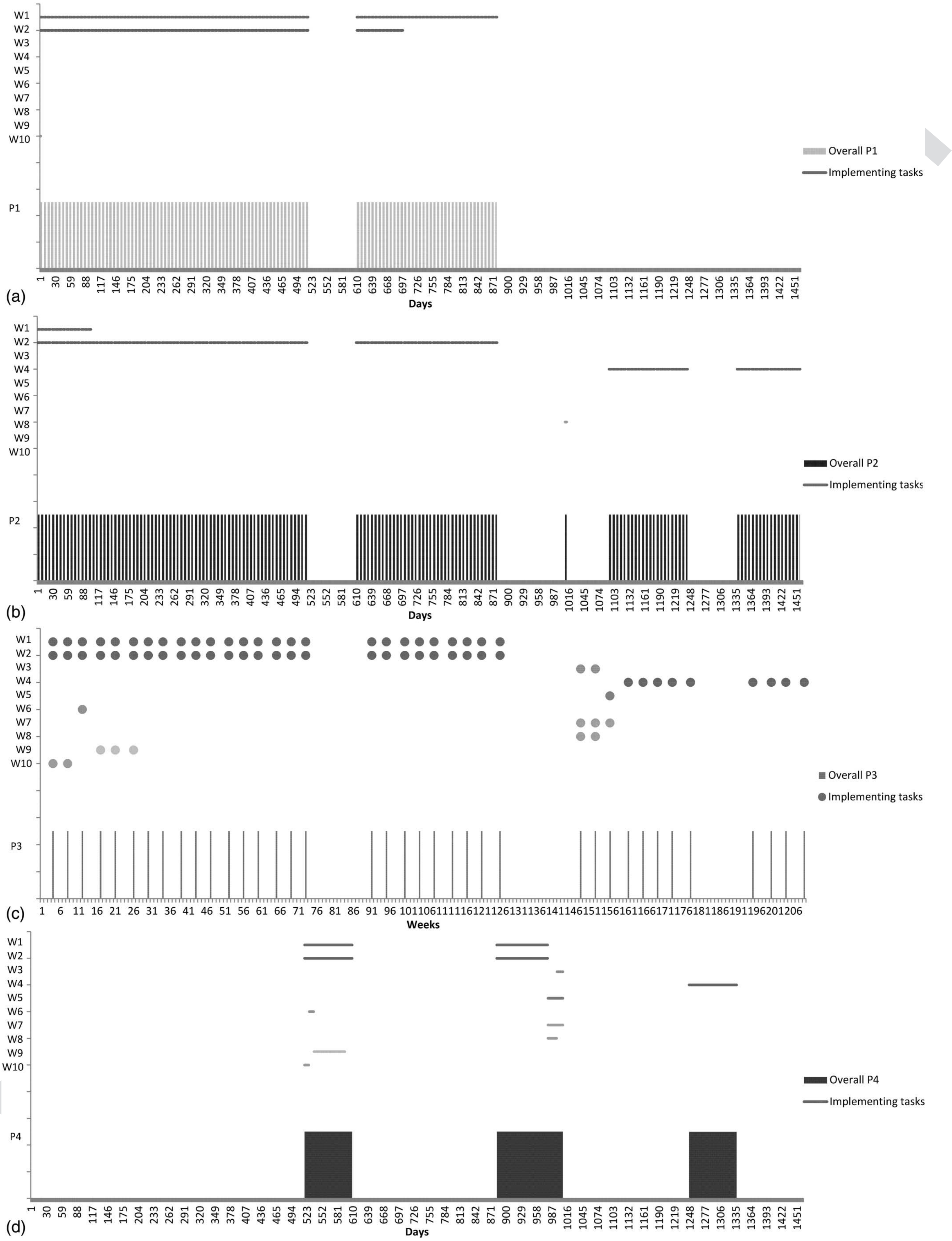
Sensitivity to Labor and Machinery Costs

To show the sensitivity of the solution to the labor and machinery cost, the proposed model was tested on Scenario S1 with only one

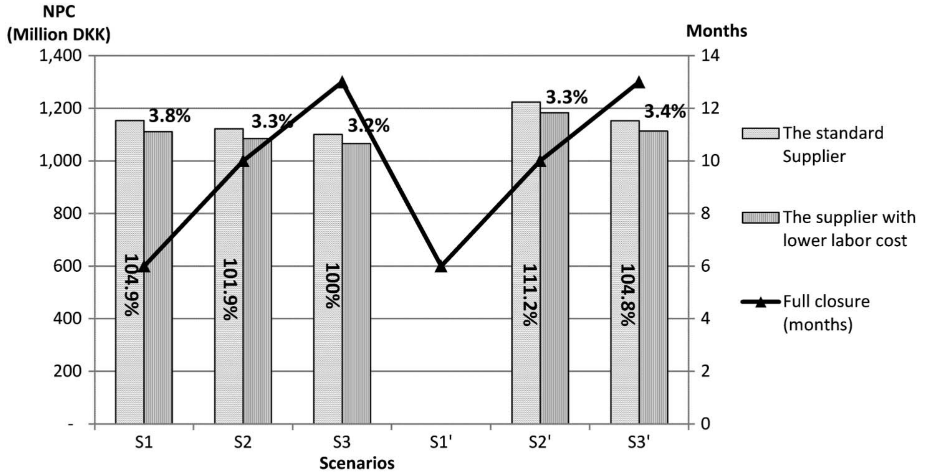
Table 5. Summary of the Computational Results on the Six Scenarios with the Two Different Suppliers

	Standard supplier							Supplier with lower labor cost						
Scenario	TCC (DKK)	Gap (%)	P1	P2	P3	P4	Time	TCC (DKK)	Saving (%)	P1	P2	P3	P4	Time
Nominal	790,516,420	−28.1						731,047,532	−7.5					
S1	1,153,601,014	+4.9	2	139	183	182	0:17:39	1,110,189,679	−3.8	2	139	183	182	0:11:43
S2	1,121,044,536	+1.9	2	6	142	308	0:25:12	1,083,890,326	−3.3	2	6	142	308	1:18:06
S3	1,100,130,468[a]	0.0	2	7	111	382	2:00:00	1,064,984,501[b]	−3.2	0	0	112	381	2:00:00
S1’	Infeasible	—	—	—	—	—	—	Infeasible	—	—	—	—	—	—
S2’	1,223,804,429	+11.2	564	732	38	308	0:01:22	1,183,032,558	−3.3	564	732	38	308	0:02:43
S3’	1,152,450,381	+4.8	113	561	35	399	0:02:00	1,112,880,823	−3.4	74	630	35	399	0:01:23

[a]Final solution provably within 0.37% from optimality.
[b]Final solution provably within 0.33% from optimality.



F3:1 **Fig. 3.** Track possession schedule for Scenario S2' indicating, for each possession type, which tasks are performed and when they take place:
F3:2 (a) interval possession (P1); (b) night possessions (P2); (c) weekend possession (P3); (d) full-closure possession (P4)



F4:1 **Fig. 4.** Total construction costs comparison

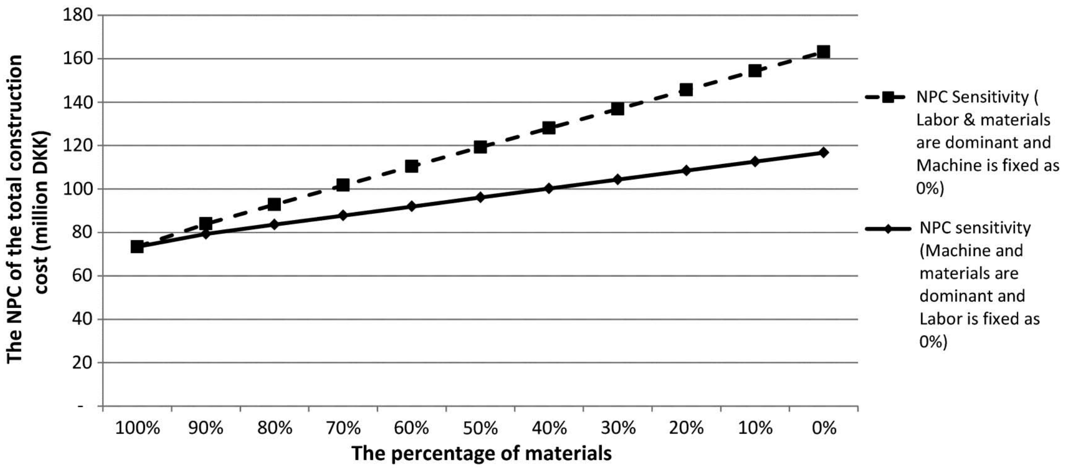
task (W1: earthwork) included. The input percentages of materials (i.e., R_1^{Mat}) was changed, ranging from 0 to 100%. Once this percentage is fixed, the model is tested, first with $R_1^{\mathrm{Mac}} = 1 - R_1^{\mathrm{Mat}}$ and $R_1^{\mathrm{Lab}} = 0$, and then with $R_1^{\mathrm{Mac}} = 0$ and $R_1^{\mathrm{Lab}} = 1 - R_1^{\mathrm{Mat}}$. The results are given in Fig. 5: the solid line corresponds to the TCC when $R_1^{\mathrm{Lab}} = 0$, and the dashed line to the TCC when $R_1^{\mathrm{Mac}} = 0$. The real total cost is in the range between the two lines illustrated in Fig. 5.

As can be seen, when the percentage of material cost decreases, the total construction cost increases. Also, the sensitivity to machinery costs is lower than that to labor costs. Because the machinery unit price is constant in track possessions, the cost increase was only due to the increased working duration by the low working productivity taking track possessions, depicted by $(\bar{p}_1/p_i^{\beta})$ in Eq. (2), whereas, labor costs depend not only on $\bar{p}_1/p_i^{\beta}$ but also on f^{β} (i.e., the extra labor wage in nonnormal working hours) as defined by Eq. (3). Therefore, when the cost of a task mainly comes from labor and machinery costs (such as W2 and W5), it is crucial to wisely choose track possessions or the TCC could quickly increase. On the contrary, when the cost of a task is dominated by material costs (such as W7 and W8), it could be beneficial to implement them in the track possession with minimum interruption to the existing transportation services (e.g., P1 and P2).

Conclusions

This paper has considered the RTPSP in which a large-scale railway infrastructure project involving multiple construction works is to be planned. The problem is to determine the time and the track possessions to execute the tasks within the given railway track blocking proposal over the planning horizon of 4–5 years. Four typical track possessions (i.e., interval, night, weekend and full closure) were considered. The proposed approach first computes track-possession-based real prices derived from nominal market prices of standard working hours, and then finds an optimal (or near-optimal) solution by solving a MILP formulation of the problem having minimum total construction costs.

The applicability of the approach was demonstrated on a real-life case study, provided by the Danish national railway infrastructure manager, including the Fehmarn Belt railway upgrade project between Vordingborg and Rødby in Denmark with a length of approximately 55 km. Six different scenarios were investigated to compare three track blocking proposals for each of two types of construction providers. The results showed that it is necessary to transfer nominal market prices into track-possession-based real prices to reduce the risk of budget overruns; indeed, up to 28% of the total construction cost was due to track possessions. The proposed approach was able to find solutions that are provably within 0.37%



F5:1 **Fig. 5.** Sensitivities of NPC as function of the percentages of labor and machine from optimality in 2 h of computing time for the scenarios for which a feasible solution exists. Yet the results showed that the overall construction cost could be decreased (up to 11.2%) by giving a track closure plan with longer weekend and full-closure possessions. Furthermore, the comparison between the two types of construction providers showed that choosing a construction supplier with a labor cost cheaper by 35% translates into an overall saving of only up to 3.8%. Finally, a sensitive analysis of the ratio between labor and machinery costs and possible budget overflows indicated that material-dominated tasks are less sensitive to track possessions than labor- or machinery-dominated tasks; for the latter tasks, track possessions should be carefully chosen.

As for future research, the authors can envision potential improvements in two different areas: (1) extend the solution approach by including passenger losses due to the different track possessions; and (2) enrich the MILP formulation by considering the physical locations of the construction tasks and corresponding interactions to achieve a more precise estimation of the maximum number of simultaneous tasks to execute.

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Paper 4

Framework for Railway Phase-based Planning

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Framework for Railway Phase-based Planning

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Abstract

In the railway field, planning the maintenance and renewal strategy from Life Cycle Cost (LCC) perspective gets more and more attentions recent years. The new approach looks at all the costs through the infrastructure life span and use the annuity (continuing payment with a fixed total annual spending) to evaluate the project alternatives. The comparison result can identify the most cost-efficient solution in a long run and therefore reduce the overall costs.

This article defines a phase-based framework to guide the railway maintenance and renewal project planning at strategic level. The framework evaluates the project options from a larger LCC scope: The costs from Train Operation Companies (TOCs) and passengers, together with the maintenance and renewal costs from Infrastructure Managers are included in the calculation.

The framework simplifies the planning processes and the LCC calculation into 7 phases. By going through the phases, the project's key evaluation indicators such as track quality and life time, the LCC annuity, Cash flow and Cumulated NPV curve over years, can be visualized into charts, so that the alternative proposals can be easily illustrated and compared.

A case study is introduced in the article to demonstrate how the framework works to compare timber sleepers and concrete sleepers from strategic planning level. Two Life Cycle Cost oriented policies are discussed to illustrate: high quality track is necessity to improve the cost efficiency of railway maintenance and renewals.

Keywords: Railway planning, Life Cycle Cost, Framework, Phase Based Planning, Decision Support System

1. Introduction

1.1. Background and Challenges

The railway is an important and sustainable mode of transport helping millions of passengers daily. Railway infrastructure maintenance and renewal (M&R) becomes a worldwide challenge [1]. An increasing performance is required by government and Train Operation Companies (TOCs), such as more trains per hour, longer operating hours and better punctuality. On the other hand, it conflicts with the increasing budget pressures and operational restrictions [2]. Infrastructure Manger (IM) has always to find a way to improve the project cost efficiency.

As a response IM has started to look at all the costs through the infrastructure life span and use Life Cycle Cost (LCC) principle to evaluate the railway maintenance and renewal projects [3]. This approach can help to identify the most cost-efficient solution in a long run and therefore reduce overall costs [4].

However, how to estimate LCC is a complex and time consuming task. It involves many factors such as track degradation rate, infrastructure life time, potential train delays due to track quality etc. A heavy data collection and analysis are needed to make the estimation. It requires a toolkit to simplify the planning processes, convert the factors into monetary values and estimate the proposals' costs from LCC perspective.

1.2. Motivation and Objectives

An early analysis of Rail Net Denmark (*Banedanmark*) states that the average age of the rail track in Denmark is too high, with a current average age of 24 years compared to the recommended 20 years [5]. It means that a big amount of the track renewal and maintenance work has been planned or will be planned in the coming years. In practice, IMs are going to make many similar planning decisions. A transparent planning tool with the previous data and experiences can contribute to the later project planning.

The objective is to develop a so-called "Railway phase-based planning framework" to help decision-maker, from the Life Cycle Cost (LCC) perspective, to plan the railway infrastructure project more economically.

2. Life Cycle Cost Assessment

2.1. Life Cycle Cost

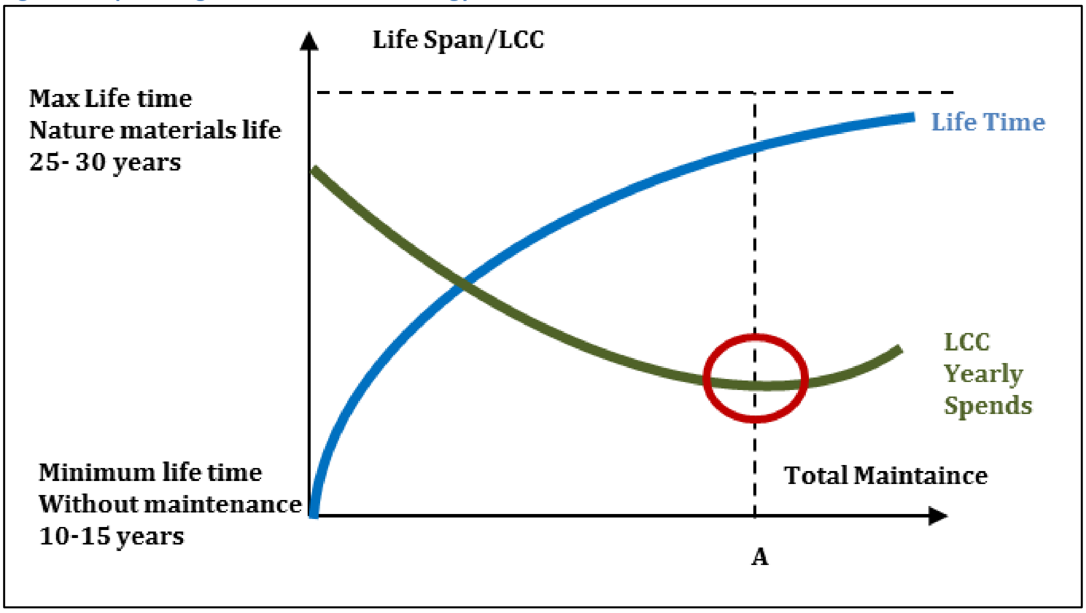
Life Cycle Cost (LCC) is a main principle of economic investment evaluation. It counts all costs from one investment until the next re-investment. LCC is more and more popular to evaluate the railway infrastructure project [6]. The LCC annuity, continuing payment with a fixed total annual spending (table 2), has been calculated through life span to assess the infrastructure project alternatives. In the recent years, the main LCC approach in the railways is to extend infrastructure life time through a better maintenance strategy. So the slightly-increased total spends with a longer life span can result in a better yearly expense. The new track maintenance strategy in Netherlands, as a good example, shows that it can lead to at least 10% reduction of forecasted budget [2].

2.2. The Limitations of the Existing Approach

LCC concept is under developing in railway field. The most of the focuses are still limited to the direct-costs, so-called 'planned costs', such as construction, maintenance, renewal costs and disposal values. It leads to an under-estimation without counting the 'non-documented costs' or 'un-planned costs' such as train delays, emergent track reparations caused by poor track quality which are definitely costs, but the exact value is either uncertain or not transparent during the planning. As a consequence, reducing maintenance was widely accepted in 1990s. Many governments, for the short term saving, cut the maintenance budget drastically. It caused punctuality problem of the railway system [7] a couple of years later. In the long run, the later costs, for instance track reparation and clearing the delayed traffic, were unfortunately more expensive than the early savings. Therefore, it is important to extend the LCC, including 'non-documented costs' or 'non-planned cost' by using appropriate procedures to measure uncertainty, when plan the railway long term M&R strategy [8].

Additional, other optimization today is dealing with the trade-off between renewal and maintenance. It is based on the analysis that the LCC yearly spends curve shown in the following Figure 1. The infrastructure life time can be prolonged through increasing maintenance. But it can't be infinitively extended due to nature materials life. So there exists a LCC minimum yearly spends Point A.

Figure 1 - Optimizing the Maintenance Strategy

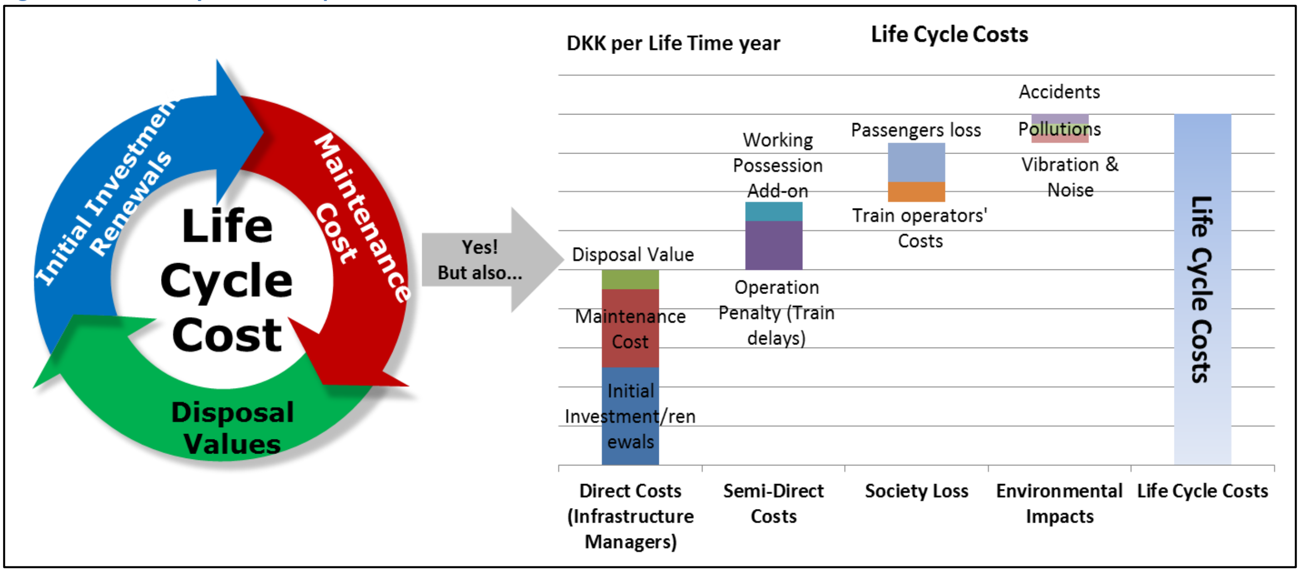


However, when the focus is still on IMs, it is again risky to under-estimate the overall costs. The maintenance itself takes away the line availability. The closure of railway lines by the maintenance purpose also takes away the track availability and brings loss for passengers and TOCs, especially at the heaviest railway sections like central station. The cost of a simple tamping maintenance for example is no longer 150 DKK per track-meter [9], but much more than that. The increasing maintenance will not result in the decreased LCC yearly spends in such case. Therefore the basis of the optimization is not suitable any more. Instead the larger scope of LCC including the preferences from IMs, TOCs and Passengers are needed.

2.3. A Broader Life Cycle Cost Scope

This is an important new progress in this paper to acknowledge a broader LCC scope, including the non-documented semi direct and indirect costs. The extended LCC is illustrated as following Figure 2,

Figure 2 - The Life Cycle Cost Scope



Direct Costs: It includes the IMs' costs like renewal costs, maintenance costs and disposal values. Disposal values could be either positive (for reuse purpose) or negative (waste disposal). Direct costs can be planned in advance and the unit price is more or less fixed.

Semi-Direct Costs: Working possession costs and operation penalty are defined as semi-direct costs. The unit price of this cost-type is not fixed but different from project to project. It depends on many pre-conditions, for example working possession costs depends on the possessions time, work type and working shifts. The same amount of track maintenance can cost quite differently among working at nights, in weekends or on daytime. The costs can only be calculated after the detailed working plan was finalized; Operation penalty is the virtual costs related to the track quality. It includes the costs of un-planned track reparation and train delays loss. Many conditions such as the drainage system, alignments, traffic loads, weather etc. can impact the calculation.

Society Loss: The new framework suggests include the passenger loss and train operations' costs during project planning. When the track quality is under threshold, the rolling stock speed is normally restricted to secure the railway safety. In such case, passengers spend more travel time. TOCs have to sign more trains into service. The society loss could be the key factor to impact the track maintenance and renewal strategy, especially for the most intensive railway sections.

Environmental Impacts: It is the cost-type imported from road construction planning field. The infrastructure maintenance strategy can also impact the environment by CO2 pollutions, vibration & noise and accidents. It can be looked as the additional penalty to the M&R alternative plan in which the track tamping and grinding are not enough.

Capital Costs: Railway infrastructure can last long time so the railway M&R planning is similar to the long term investment financially. It is necessary to include the capital costs for all the above 4 cost-types. The LCC yearly spends should then be replaced by the LCC annuity (ANN) which is shown in the following table.

Table 1 - Annuity Formulas

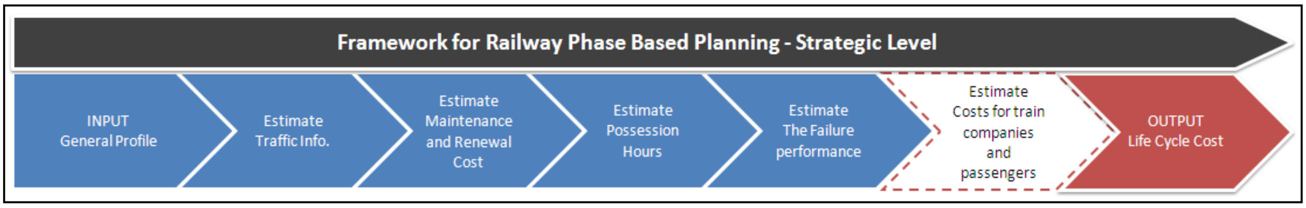
Formula	Definition and Explanation
$NPV = \sum_{a} \sum_{y=0}^{n} \frac{C_{y,a}}{(1+i)^y}$	The Net Present Value *NPV* is the sum of the discounted Life Cycle costs *C* during all years (*y*) and for all activities (*a*). Year n is the last year, The interest rate (*i*) applied.
$ANN = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \cdot NPV$	Annuity *ANN* is any continuing payment with a fixed total annual amount. It is calculated in multiplying the net present value with the capitalizing factor (*CF*) $CF = \frac{(1+i)^n \cdot i}{(1+i)^n - 1}$

3. The Framework For Railway Phase-Based Planning

Life Cycle Cost estimation is complex because any small change to the M&R plan can impact the final LCC annuity. For instance, if the track tamping interval is extended from 2 years to 3 years, all the 4 cost types and the infrastructure life time will change (Direct cost and life time decreases; semi-fixed cost and society cost increases). It could result in an either better or worse LCC annuity. In the other words, any small improvement in planning could result in a better LCC. The phased-based planning framework is therefore developed to help IMs to find out a cost efficient strategy.

The tracks and switches account for about 60% of the total maintenance and 80% of the renewal expenses [10], The Framework is mainly to plan the strategic (+5 years) track system maintenance and renewal work. The Life Cycle Cost estimation is defined into the following phases.

Figure 3 - Framework Phases



3.1. Phase 1: Input General Profiles

Phase 1 is the starting step where the line profiles are documented. Such as,

- Length of the line
- Max axel load
- Number of track sections
- Number of Switches and Crossings (S&C)
- Rolling Stock speed range
- Sub-structure condition
- Ballast, sleepers, rails, fastening type etc.

Some of above data are used to calculate the traffic loads, track quality, life time in the following phases. The other information is for documentation purpose. Generally, it provides the project overview.

The many estimates described below are typical non-documented and rather uncertain by nature. This calls for subjective expert evaluations. However such evaluations are subject to serious pitfalls, for example wishful thinking, over optimism, lack of knowledge, etc. The type of analysis in this paper is exposed triple or more, because 1) two alternatives are compared, 2) benefits and costs are divided, 3) because of the rather long time horizon, and 4) the result is exposed to future political decisions. It is advocated to use scientifically based and accurate evaluation procedures which has documented to cope with such pitfalls [14][15][16].

3.2. Phase 2: Estimating Traffic

This phase is used to estimate the average load on the infrastructure. The gross tons per year can be calculated in the traffic profile table which includes,

- Number of passenger trains per day
- Number of freight trains per day
- Weekend traffic rate
- Traffic increase rate per year
- Rolling stock conditions
- Operation hours
- Average passengers per train etc.

Some data requires the coordination from TOCs, such as average passenger per train, rolling stock condition etc. It therefore involves the TOCs at early planning stage.

The rolling stocking condition is included because the bad wheel condition can increase the rail wear rate. It indirectly increases the maintenance requirement. It’s better to know it in advance before drafting the maintenance plan. The passenger-kilometer per day is also calculated to indicate the passenger loss during the maintenance. It is another important factor that can impact the maintenance scheduling decision.

3.3. Phase 3: Planning Maintenance and Renewal

Phase 3 consists of an estimation of the periodic maintenance (major works, such as rail grinding and track tamping, with intervals of more than a year) and partially renewals. The M&R direct costs and interest rate are collected in this phase. When the track life span was estimated, the LCC annuity and down payments such as the depreciation of track value can be calculated.

To estimate the life time and track quality changes over years, the track behavior equation is quoted. Experience shows track quality degradation is a function of time and load on the track. In close cooperation with the Austrian Federal Railways (ÖBB), the University of Technology, Graz, set up a data warehouse and derive the track behavior Equation [6].

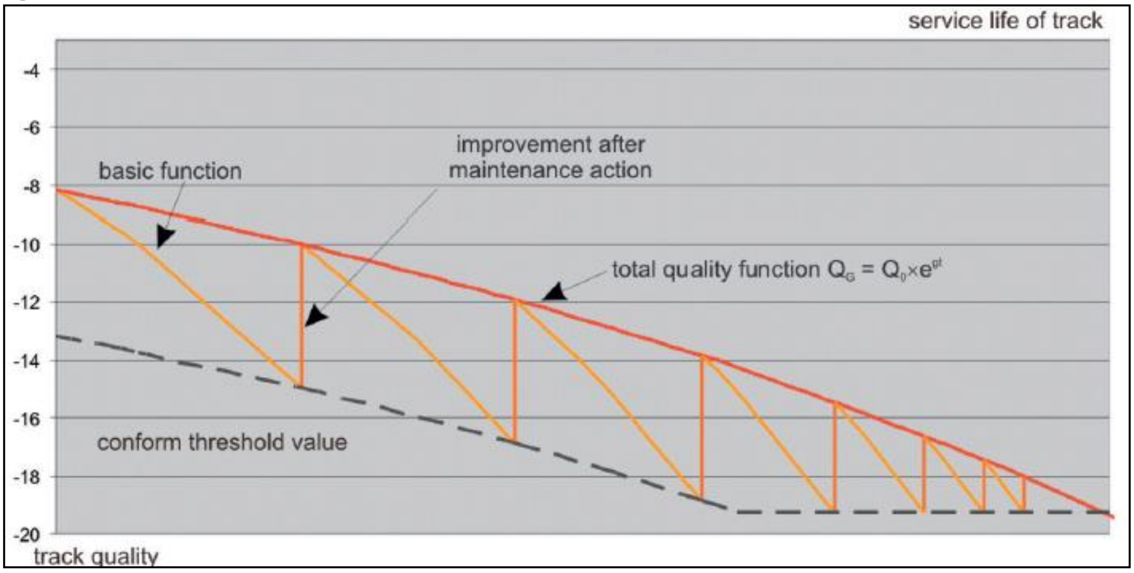
$$Q = Q_0 * e^{-b*t}$$

Where,

- Q_0 denotes the initial track quality and b is the rate of deterioration over time t.

Maintenance can increase the track quality and extend the track life time, but never result as a 'new track'. At end of the track life time, the track quality decreases fast. To protect the track quality from crossing the threshold value, it requires more frequently maintenance as illustrated in the following figure.

Figure 4 - Track Behavior



In this phase, initial track quality and threshold is estimated, track behavior functions can be built to simulate track life time. Expert experiences are highly recommended afterwards to adjust the simulation result. Because simulation could be dangerous ("rubbish in, rubbish out!"). Experience shows that allowing experts evaluate the issues, while using a relevant procedure yields often better results, than simulation, where it is difficult to control the entire procedure [16]. Switches and Crossings are one of the main components that impacts the maintenance cost. It is recommended to include them as well. As output, the yearly depreciation of track value and maintenance annuity is calculated from this phase.

3.4. Phase 4: Possession Time Estimating

Based on the maintenance and renewal estimation from Phase 3, the total net possession shift can be estimated in Phase 4. The working time should be round up to working shift hours. The railway project normally plans in this way in the practice. For example, a 3 hours night work actually costs as 7 hours night work shift. The short working time easily results in a higher price for the maintenance.

The possession time estimating is based on the assumption of M&R working speed. Thus it is crucial to collect the detailed practical data. As results, the total possession time in calendar days, working hours are calculated; the M&R annuities are adjusted in this phase.

3.5. Phase 5: Estimating the Failure Penalty

Phase 5 is to estimate the delay penalty based on the track Reliability, Availability, Maintainability and Safety (RAMS) as defined in the following table [11]. The delay penalty is estimated through the infrastructure failure and train delay simulation.

Table 2 - RAMS Definiations

RAMS	Brief
Reliability	Reliability can be calculated by using the predict failure approach. The failure probability indicates the reliability %.
Availability	Availability is indicated by the ranking of the total planned possession time per year in the reversed order.
Maintainability	Maintainability is to indicate how fast the track can be repaired.
Safety	Safety has many definitions. Here the track threshold value indicates the Safety level.

The main assumptions, such as average delay minutes per train, average cancellation, number of delay trains per failure, Mean time between failures and Penalty rate under threshold, have to been made in the phase. The same as in Phase 3, S&C is also important to include into the calculation in Phase 5.

3.6. Phase 6: Estimating the costs for Train Operators and Passengers

Passenger Loss: The way to calculate passenger loss is based on Value of Time (VoT) for delays. The train cancellation can be looked as a much delayed train. The framework suggests the following formula to calculate the potential loss for passengers.

$$Passenger\ Loss = Cumulative\ Delay\ Hours * Number\ of\ passengers * VoT$$

However different type of passenger has different time values. There are many statistics showing VoT in Denmark for public transport [12]. The assumption of the average railway passenger VoT has to be made according to the time period and passenger types.

Table 3 - Value of Time for public transports

Value of Time	Unit	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*
Unit Value of Time - Public Transport								
Travel Time								
Household	kr./hour pr. person	80	76	77	78	80	81	83
Employee	kr./hour pr. person	338	322	325	329	335	342	350
Others	kr./hour pr. person	80	76	77	78	80	81	83

TOCs' costs: Additional costs generated at the TOCs' side due to the railway M&R operation, such as the administration costs to plan the alternative routes, renting train-buses and announcing the changes. It also includes the potential TOCs' loss like the revenue loss due to reduction of number of passengers in both long term and short term, putting additional trains into service when the rolling stock speed is restricted, additional rolling stock maintenance due to bad track quality and so on. Meanwhile these various costs are likely to be biased through wishful thinking, tactical reasons, or one of the many pitfalls while evaluating most uncertain values [16]. It needs a further investigation and systematic approaches to estimate them with train operators.

3.7. Phase 7: Output the Overview of the Life Cycle Cost Annuity

After going through all the previous phases, Phase 7 reaches the 4 main outputs to give the overview,

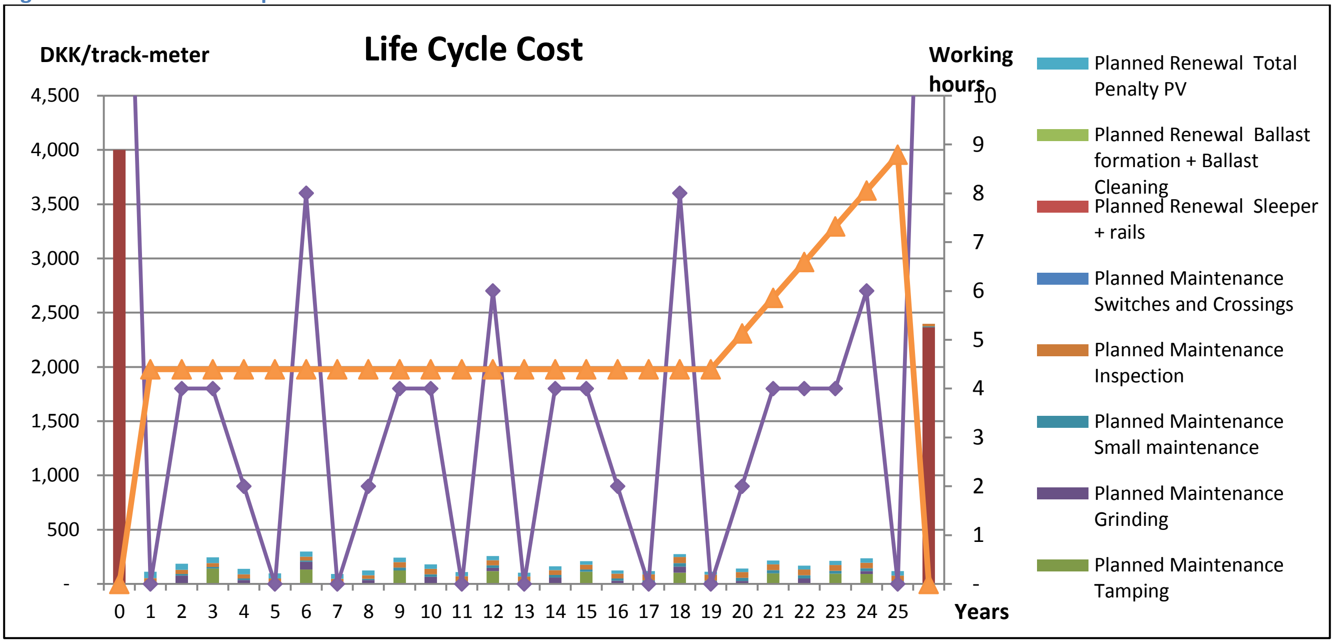
- Track Behavior chart (Figure 6)
- LCC Annuity chart (Figure 7)
- Cash Flow curves (Figure 5)
- Cumulated NPV chart (Figure 8)

Track Behavior Chart is to show the track quality over years and maintenance actions.

LCC Annuity Chart is the chart where all alternatives can compare to each other. It includes the initial investment depreciation, the maintenance and renewal LCC annuity, the potential penalty caused by the potential infrastructure failure and the total amount of net possession time per year.

Cash Flow curves illustrates the cash flow in life span. Besides the cost information, the possession time per year is also included in the chart to give reference.

Figure 5 - Cash Flow Example



Cumulated NPV chart is to show the cumulated value of investment through years. It mainly used to compare similar alternative solutions.

4. Case Studies

4.1. Concrete sleeper vs. Timber sleeper

Due to the greater weight which helps to remain in the correct position longer, concrete sleepers have some advantages such as, a longer service life and less maintenance; the concrete fastenings were cheaper and easier to obtain than timber and better able to carry higher axle-weights and sustain higher speeds.

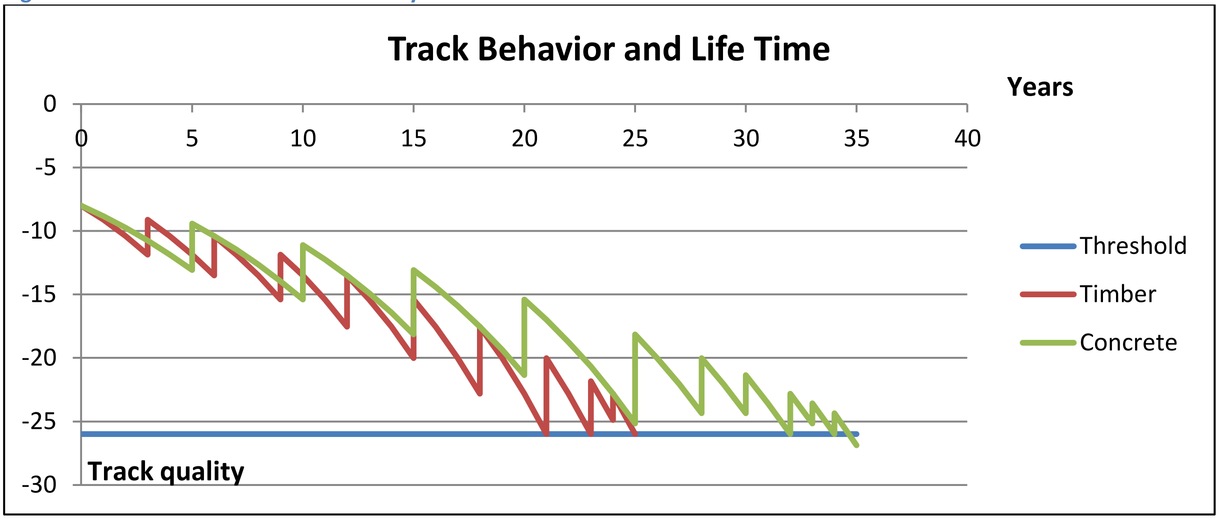
While concrete sleepers are more expensive and also have other disadvantages: when trains derail and the wheels hit the sleepers, timber sleepers tend to absorb the forces and could be reuse, while concrete sleepers have to be replaced; concrete sleepers are heavier and it requires heavy logistics transport. To compare two types of sleepers from LCC, the assumptions are made in the following table,

Table 4 - Main assumptions

Items	Concrete	Timber
Service Life (years)	35	25
Price (DKK per track-meter)	4.500	4.000
Tamping every	5 years	3 years
Reaching threshold years without maintenance	12	9

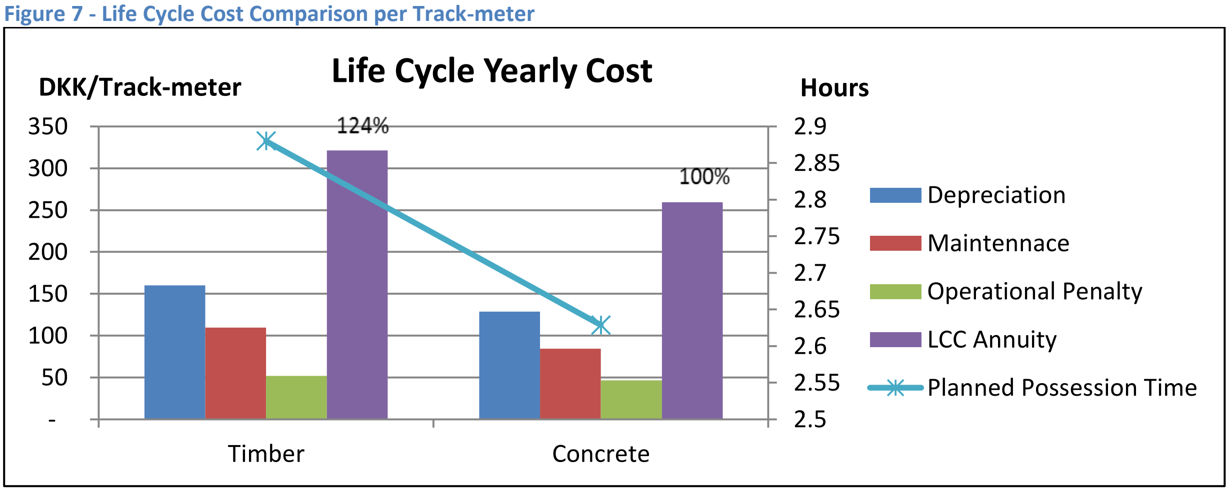
By using the phase-based planning framework, the life time can be simulated for two solutions. Green curve states the concrete sleepers and the red curve shows the timber sleepers [13].

Figure 6 - Track behaviors for two track systems



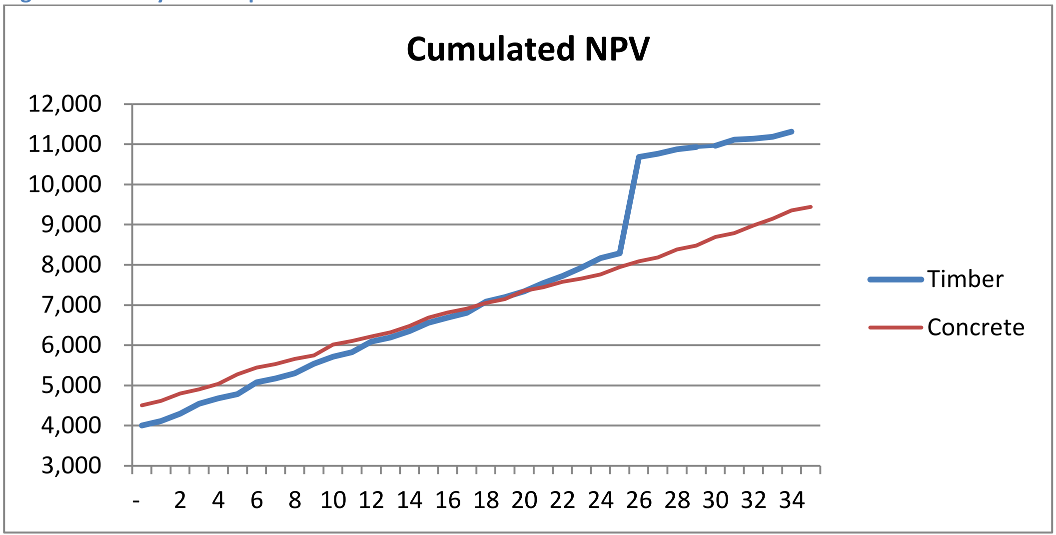
The initial track quality of timber sleeper has been set the same as, namely the concrete one for comparative analysis purpose. The interest rate is a sensible value. Many interested parties prefer different values due to scarce investment capital. A 'political bias' is often be present here [16]. In this case, the interest rate is set to 2%. The LCC annuity is calculated based on this value. It is highly recommended to do sensitivity analysis afterwards.

Figure 7 - Life Cycle Cost Comparison per Track-meter



Concrete sleeper is a worthy investment from LCC perspective. Timber sleeper would be 24% more expensive than concrete sleeper. The cumulated NPV curves can be seen as following,

Figure 8 - Life Cycle NPV per Track-Meter



Concrete sleeper is more expensive to construct. But it requires less maintenance work and has longer life span. Timber sleeper solution is cheaper at construction but becomes more expensive after 20 years due to its higher maintenance costs and it becomes even more expensive after renewal at the end of its life span 25 years.

4.2. LCC Oriented Policy discussion

High quality track + less maintenance vs. Low quality track + more often maintenance

Let's compare the following two policies,

- High quality Track: Install high quality track with maintenance every 5 years
- Low quality Track: Install low quality track but maintain it every 3 years

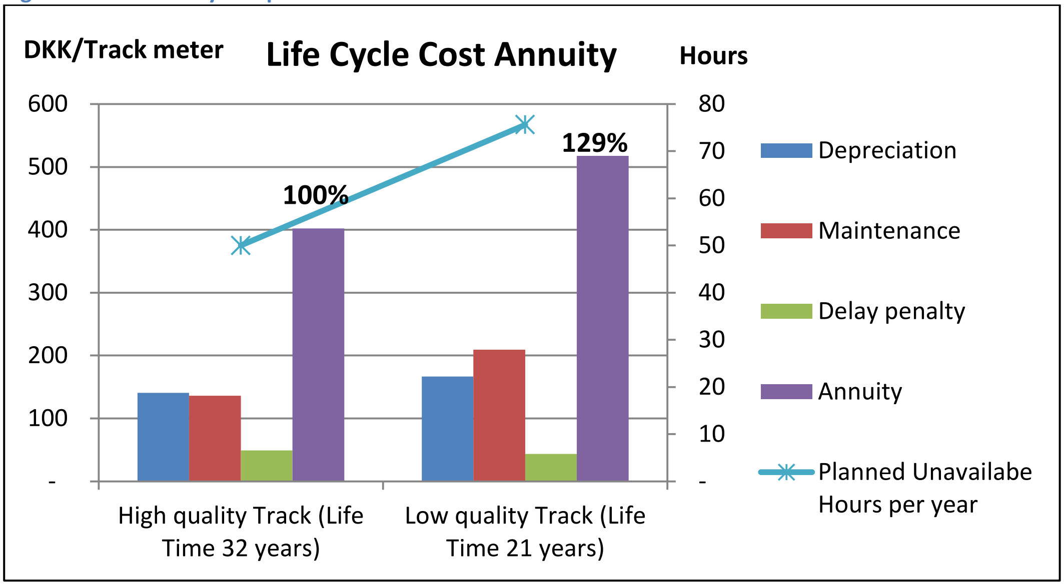
Based on the following assumptions, and the outputs from the framework, it concludes that even the low quality track alternative have higher frequency of maintenance, it still ends up with the shorter service life. It is more expensive (129%) to build and maintenance the low quality track.

Table 5 - Main Assumptions

Interest Rate	2%	
Gross Maintenance cost	900	DKK/meter
Average delay minutes per train	5	minutes
Average Cancallation factor	20	minutes
DKK per delayed train-hour	10,000	DKK
DKK Per cancelled train-hour	30,000	DKK
Line Length	5,000	meter
Double Track	yes	

Initial Quality	**Low**	**High**
Initial Investment (DKK/T-meter)	3,500	4,500
Maintenance - amount of tamping in life time (times)	6	7
Delay penalty (DKK/T-meter)	43	49
Life Time	21	32
Annuity	**518**	**402**

Figure 9 - LCC annuity comparison



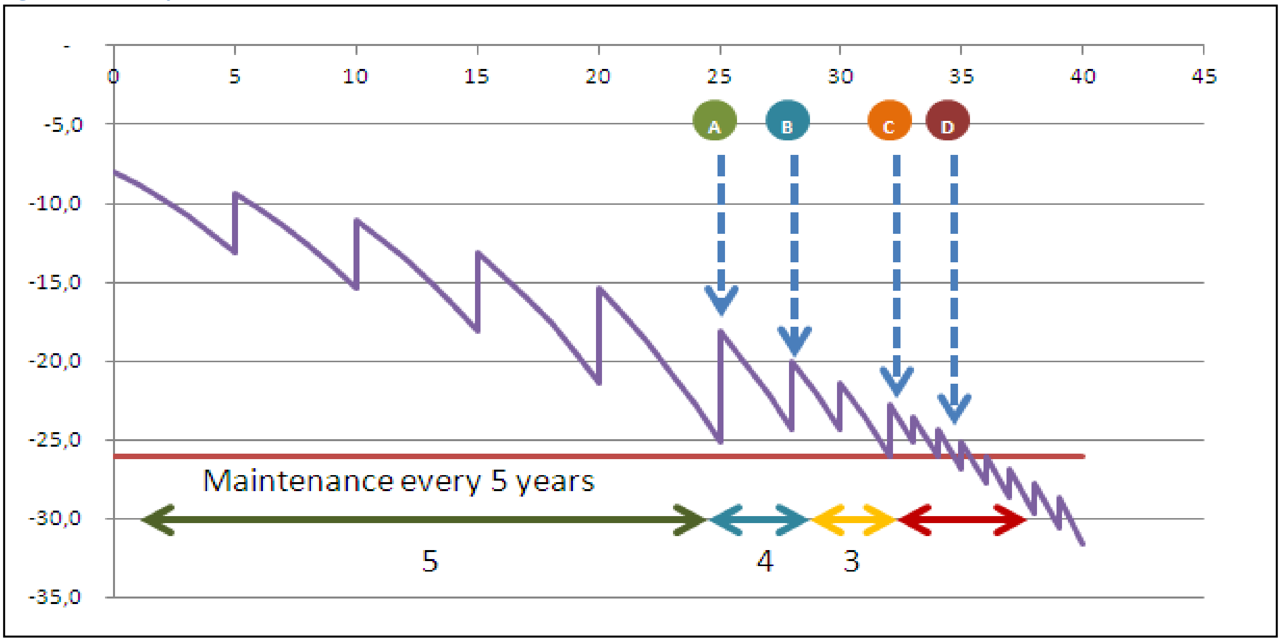
This conclusion leads to a high quality track strategy. Installing high initial quality with reduced maintenance costs is much more efficient. High quality track is not only technically essential but also economically necessary from LCC perspective.

Positive track renew vs. Maintenance

Track maintenance improves the quality but it can never reach the new track quality. The following figure shows the track behavior under 5 years' maintenance interval. When approaching the threshold value, minimum safety requirement force IM to maintain the track more often.

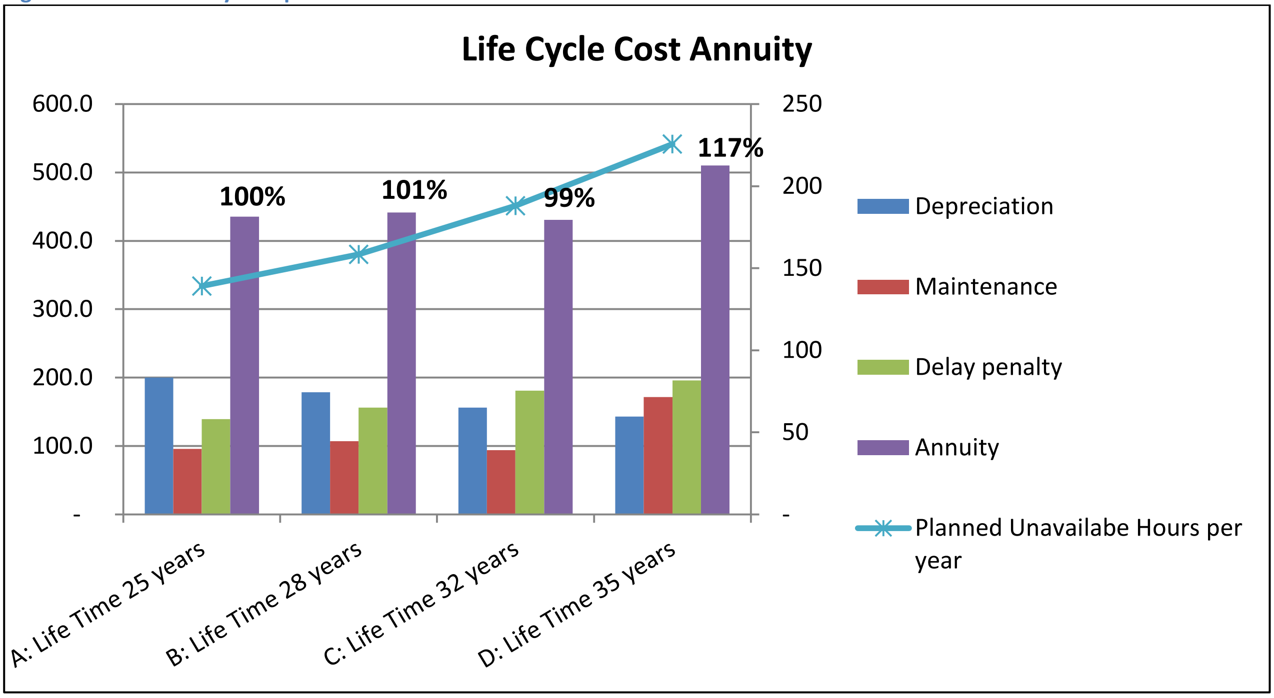
To answer the question: When should the track system be totally renewed? 4 time points (A-D) are selected in the following figure.

Figure 10 - Time points to renew the track



From the LCC annuity comparison, it concludes that it is not the best that re-installing the track system too often. Maintaining the track until to the time point where yearly maintenance is required is the most economical solution in this case.

Figure 11 - LCC Annuity Comparison



5. Conclusion

Maintaining and renewing rail infrastructure (M&R) becomes a worldwide challenge. An increasing performance is required by government and train operators, such as more trains per hour, longer operating hours and better punctuality. On the other hand, it conflicts with the increasing budget pressures and operational restrictions. A decision support toolkit is required to help Infrastructure Managers to improve the project cost efficiency. Additionally, planning railway infrastructure projects, Infrastructure Managers have to make many similar decisions, such as choosing the infrastructure component; deciding the maintenance intervals; and scheduling renewals. A general planning framework for enhancing the transparency, best practice sharing and documentation is needed.

A phase-base planning framework is therefore developed to support railway decision making at the strategic level. It integrates the Life Cycle Cost approach and simplifies the planning processes into 7 phases. It can help Infrastructure Managers to evaluate alternative proposals and identify the most cost-efficient solutions from the LCC perspective. However evaluation pitfalls are especially damaging for a relevant result in these analyses. It is due to the LCC principle and the long time frame. This calls for the use of evaluation procedures which are able to cope with these pitfalls [14][15][16].

A case study is introduced in the article to demonstrate how the framework works to compare timber sleeper and concrete sleepers from strategic planning level. Two Life Cycle Cost oriented policies are also discussed to illustrate: the high quality track is not only technically essential but also economically necessary to improve the cost efficiency.

List of Abbreviations

IM	Infrastructure Manger
LCC	Life Cycle Cost
M&R	Maintenance and renewal
NPV	Net Present Value
RAMS	Reliability, Availability, Maintainability and Safety
S&C	Switches and Crossings
TOCs	Train Operation Companies
VoT	Value of Time

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Paper 5

The potential cost from passengers and how it impacts railway maintenance and renewal decisions

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The potential cost from passengers and how it impacts railway maintenance and renewal decisions

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Abstract

To plan Maintenance and Renewals (M&R) for the heavy railway lines, scheduling work possession time and deciding the closure of railway line are quite challenging for Infrastructure Manager (IM) at tactical planning level. As usual, the direct costs such as the materials costs, man power price and machinery costs are the important factors for IM to evaluate all the alternative schedules. At the same time, the potential cost from passengers is also crucial to minimize the impacts to the society.

A phase-based planning toolkit is developed to help IM to plan and compare project proposals from a wider cost scope, integrating the passenger loss and direct costs into the comparison at planning stage. Passenger loss is estimated basing on the potential delay time values.

The case study shows the potential cost from passengers is one of the key factors impacting the rank of M&R options. It even dominates the overall cost comparison for the busiest railway stations. In such case, the track closure time has to be decided according to the passenger loss instead of the direct costs. Sometime the best proposal for society might be the most expensive solution for IM. Therefore the potential passenger loss is not something that can be ignored at planning stage.

Keywords: Passenger Costs, Railway Maintenance Planning, Railway Closure Time Evaluation

1. Introduction

1.1. Background

Infrastructure Manager (IM) has been separated from the restructuring of railways in the last decades (1997 in Denmark). The objective of restructuring is to make railway more competitive. It mainly brings the following challenges to infrastructure managers.

Firstly, the better performance such as more trains per hour, longer operating hours and better punctuality is required by government and Train Operation Companies (TOCs). More Maintenance and Renewal work are needed to remain the railway infrastructures in good order.

Secondly the restructuring transfers the rail network ownership to IM so that the focuses can be put on the railway infrastructure. The cost oriented policy was made for IM to improve the project cost efficiency. Under the increasing budget pressures, costs therefore become the most important factor impacting the choice of M&R implementation.

At last, railway as the most safety reliable traffic mode transports millions of passengers on daily basis. Any closure of a railway lines on the maintenance and renewal purpose can delay a lot of passengers, creates traffic congestions and further impacts to the whole society.

1.2. Motivations

When the total amount of the M&R work had been decided from the strategic planning, how to plan the possession working time and decide the closure time of the railway line are the main questions.

Limiting the analysis only on the M&R direct costs such as the materials costs, man power and machinery costs will be risky to under-estimate the railway project impacts. Because a low cost maintenance plan, for instance totally closing a line at rush hours, is not the most cost efficient solution at all for the passengers. If the railway is closed long enough, the impacted passengers could choose personal car to do the transport and leave the public transport in a long run.

Therefore it is necessary to investigate how the potential cost from passengers impacts the ranking of alternative proposals from a wider cost scope.

2. Objective and Approach

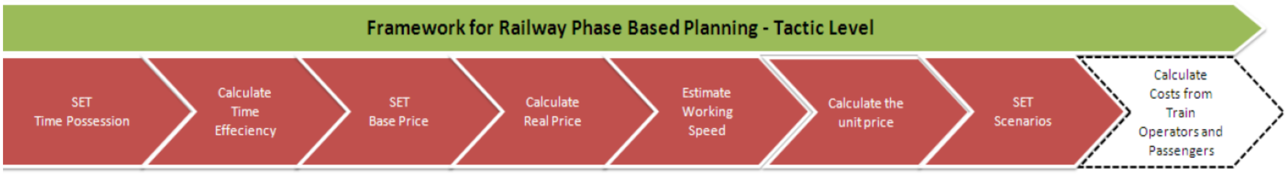
The main objective is to find an approach converting the passenger loss caused by maintenance and renewals into monetary costs. Integrating it into the cost comparison to investigate how it can impact the railway M&R decision at tactical level.

A so-called "railway phase-based planning toolkit" is developed to plan and compare the railway infrastructure project proposals from a larger cost scope. The new planning toolkit calculates the construction costs by taking the working possession time into account. The passenger loss caused by the construction work is also integrated into the analysis.

It is a phase-based approach in which different parts of the costs are calculated in separated phases. The idea is that the toolkit can be easily extended or research in details in particular phase. Passenger loss is built in Phase 8 and can be either included or excluded to the final cost comparison. How the passenger loss impacts the proposal ranking can be then investigated and discussed.

In the framework, the planning processes and cost calculation are constructed into the following phases,

Figure 1 – The Tactical Planning Phases



3.1. Direct Cost Calculations

The “Green-field market price” (the price in the situation where people work 37 hours at workdays), will be used to calculate more accurate actual spends by considering the working possessions, job type and working efficient etc… The calculation is divided into 7 stages indicated by the red arrows in Figure 1. It includes,

- Setting work possessions
- Calculating working efficiency
- Setting green field market price
- Calculating the price for each working possessions
- Estimating working speed and,
- Setting scenario and Estimating the actual costs

It is very important to do the transfer because the same amount of workload can cost quite differently in different working possessions. It estimates from Fehmarn project that the difference can be up to 10%.

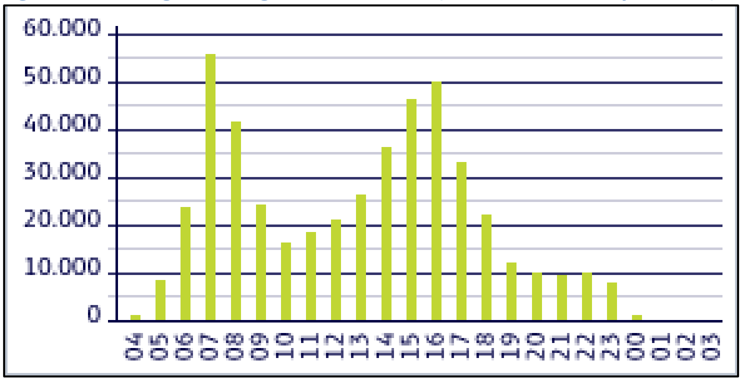
3.2. Passenger Loss Estimation

The way to calculate passenger loss is based on the potential passenger delays. Value of Time (VoT) is used to transfer the delay minutes into monetary values. The following formula is showing the calculation of the potential loss for passengers.

$$Passenger\ Loss = Number\ of\ passengers * \ Cumulative\ Delays * VoT$$

Number of passengers: It can be calculated according to the traffic density (from the passenger train timetable) and the average amount of passenger per train. The number of passengers is changing from time to time but has certain seasonality in a long term. The following chart is showing the S-train average amount of passengers at weekday in 2007. At this step, many assumptions such as passenger seasonality at implementation period, potential reduction of passengers due to maintenance, train-bus delays etc. need be made.

Figure 2 – Average Passengers at each hour (S-train at weekday in 2007)



Cumulative Delays: It means the cumulated delay per passenger caused by the maintenance and renewal in the whole implementation period. It is estimated via train delay simulation according to the detailed possession plan. For example, if the line is totally closed and the train-buses have been arranged, the additional travel time on train-buses can be looked as delays. A cancelled train can be seen as a long time delay train. Simulation normally is used to estimate the delays at this step.

Value of Time (VoT): In transport economics, VoT is the amount of money that a traveller would be willing to pay in order to save time, or the amount of money they would accept as compensation for lost time.

The passenger value of time is a complex estimation which depends on many factors like passenger type, age, income and day time etc. As an example shown in the following table, there are many statistics providing the VoT for public transport in Denmark. The average passenger VoT for particular railway project has to be estimated according to passenger type mixture and travel purpose.

Table 1 - Value of Time for Public Transports

Value of Time	Unit	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*
Unit Value of Time - Public Transport								
Travel Time								
Household	kr./hour pr. person	80	76	77	78	80	81	83
Employee	kr./hour pr. person	338	322	325	329	335	342	350
Others	kr./hour pr. person	80	76	77	78	80	81	83
Waiting time and delay time								
Household	kr./hour pr. person	160	153	154	156	159	162	166
Employee	kr./hour pr. person	675	643	650	659	670	684	700
Others	kr./hour pr. person	160	153	154	156	159	162	166
Transit time								
Household	kr./hour pr. person	120	114	116	117	119	122	125
Employee	kr./hour pr. person	506	482	488	494	503	513	525
Others	kr./hour pr. person	120	114	116	117	119	122	125

3.3. Cost Comparison

When all the direct costs and passenger loss are calculated for each possession plan, the cost comparison was normally used to identify the most cost-efficient plan. In the comparison, direct costs and passenger loss ranks the alternative proposals; the project time in calendar days is used to indicate the impact period. The comparison example chart can be seen in the following case study.

3. A Case Study

4.1. Case Brief

Two of S-train stations, *Allerød* and *Nørreport* Stations, are used to illustrate how the planning toolkit estimates the costs from Infrastructure Manager and Passengers.

Nørreport Station is the busiest station in the center of Copenhagen, serving 165,000 people on daily base. It is a main transit station connecting the intercity trains, S-trains and the Metro. At the S-train layer, there operates six main lines on both directions in rush hours.

Allerød Station is the S-train station in north of great Copenhagen, out of the urban city area. Line E is the only service line running through the station. There is no train transit in the station. Different from *Nørreport* station, the amount of passengers is small. The most passengers use the station in rush hours.

Figure 3 - S-train Network in Copenhagen

4.2. Main Assumptions

The assumption is made that a 500 meters' track and drainage system need be renewed at *Nørreport* Station and *Allerød* station. The renewal can be done through two men and one machine. The direct cost is therefore calculated in the below structure.

Table 2 - Cost Structure

Job Types	Material Cost	Machine Cost	Man power Costs	Total
Tracks and drainage	10%	49%	41%	100%

There are 4 working possession plans as shown in the following table.

Table 3 - The Settings of Working Possession Time

#	Time Possession Type		From	To	
1	Day Working In Internals	Monday - Friday	08:00		15:00
2	7 Hours Night Working	Monday - Friday	22:00		05:00
3	Weekend Working	Friday	22:00	Monday	06:00
4	Total Closure	All days	00:00		00:00

Day working in intervals: It means the renewals are implemented between running trains. The railway services are remained. The safety settlements are requires before and after every renewal work. The working efficiency is very low. It normally takes the longest days. Passengers will be partially impacted because the trains will run every 20 minutes instead of 10 minutes at *Allerød* station. It is not a feasible solution for *Nørreport* station because the interval time at *Nørreport* station is only 2 minutes.

7 hours Night working: The renewal is implemented in the night. The man power costs 200% of the market workday price; while the prices for machine and materials are un-changed. The working efficiency is relative low. Natural time loss is around 15% at night. The safety settlements are needed before and after the renewal work, twice per night. Train-buses are arranged to replace train services.

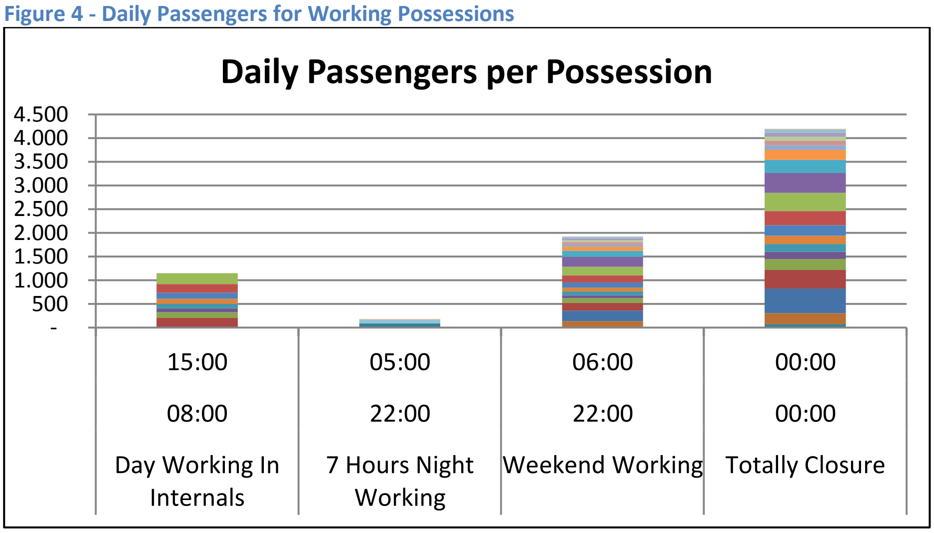
Weekend working: The renewal is implementing in the weekend. The tracks are closed from Friday evening to Monday morning. Man power costs 200% in the night and 150% in the weekend day time. There is natural time loss 15% at night. The safety settlements are required before and after the renewal work, twice per weekend. The working efficiency is relative high. Even the total working time is short but the project still takes long time in calendar days (The man and machine are still occupied between weekends). Passengers are impacted in the weekends. The train-buses are arranged to carry passengers.

Total closure: The track is totally closed for all days. The working speed is the fastest. The time loss due to the safety settlements is also the shortest. But passengers are impacted the most. They have to use either the train-bus or other transport modes to do the transport. The project can be done in the minimum calendar days. The average man power price is relative low (not equals to the green-field market price). In general, it is the cheapest solution for Infrastructure Manager.

4.3. Passenger Loss

The daily amount of passenger per hour can be calculated according to the train time table and average passengers on each train. The following table shows the result (for line E) at *Nørreport* Station.

Figure 4 - Daily Passengers for Working Possessions



The average passenger VoT per hour is estimated according to the mixture of passenger (Employee's time value is higher than household. In rush hours, most of passengers on the trains are for working purposes) and the transit activity (The value of transit time value is higher than normal travel time, at *Nørreport* Station the value of time per passenger is therefore higher than *Allerød*).

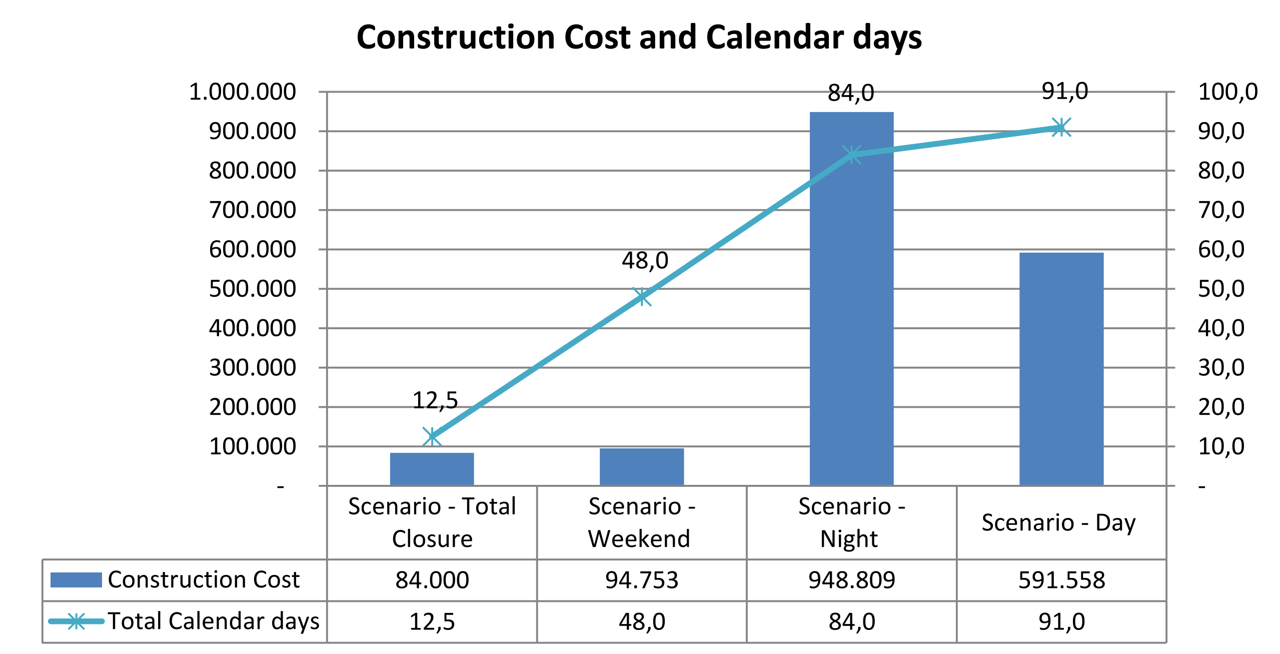
The assumptions are made that the train-bus will delay each passenger 15 minutes. When the renewal is implemented between the running trains, each passenger is assumed have 5 minute delay caused by the increased interval time from 10 minutes to 20 minutes.

The total number of passengers in general is decreasing when the train-buses are arranged to replace the existing rail service. The case study doesn't count this to keep simple.

4.4. The Comparison Results

Without taking the passenger loss into account, the direct costs comparison chart is showing in the following figure.

Figure 5 - Renewal Direct Costs Comparison



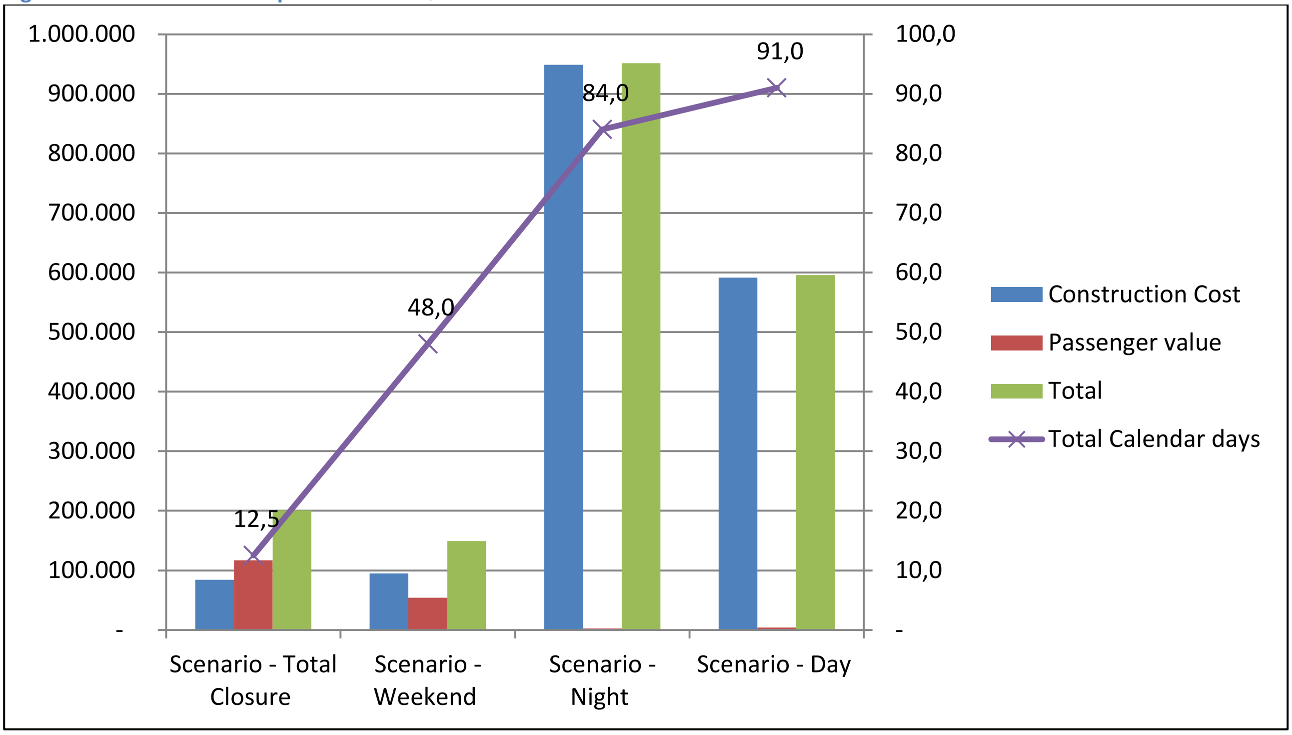
It can be concluded that,

- The solution of total closure is the cheapest solution which takes only about 13 calendar days.
- Working in the weekend is the second best option where the renewal costs is slightly higher. It takes 6.3 weekends, around 48 calendar days in total.
- Night working is the most expensive solution, more than 10 times more expensive than the total closure solution. It takes long time, 84 nights to complete the renewal work.
- Renewing the line together with the running trains is the second expensive solution but with the longest implementation calendar days.

If the passenger loss is included, it gives the different cost comparison result. At *Allerød* Station, the passenger loss is not as important as direct costs in general. The impacts only give to the total closure and weekend working scenarios. There are very few passengers in the night so that the passenger loss doesn't impact significantly. Working between the running trains keeps the passenger loss at low level but it is still a second expensive solution.

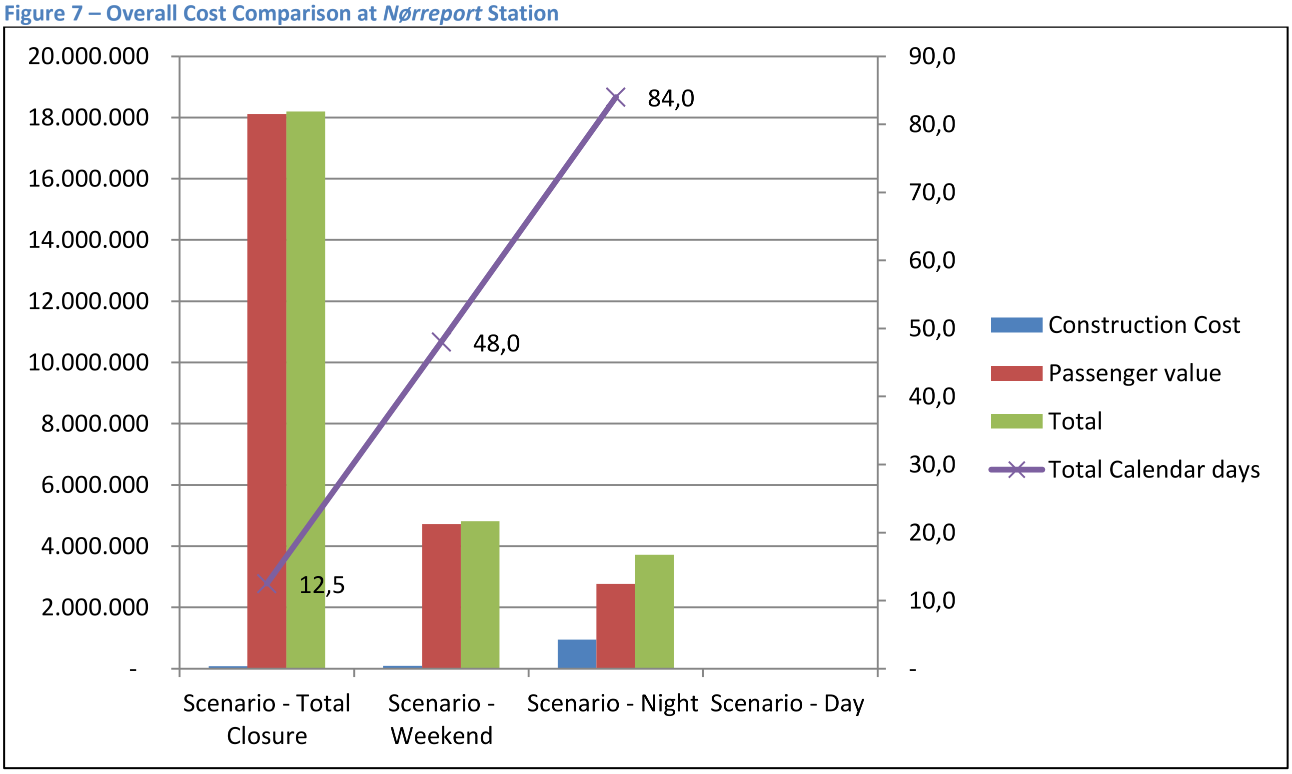
All in all, working in the weekend becomes the best solution replacing the total closure for *Allerød* station.

Figure 6 – Overall Cost Comparison at *Allerød* Station



When the traffic is heavy and the most passengers are doing transit, like *Nørreport* Station. The most cost-efficient solution is changing to night working scenario when counting the passenger loss. The following chart illustrates that the passenger loss is dominating the total cost comparison due to the higher VoT and more impacted passengers. It concludes that night working is a wise choice for *Nørreport* Station, even though it is the most expensive solution for IM.

Figure 7 – Overall Cost Comparison at *Nørreport* Station



4. Conclusion

The restructuring of railways results in an increasing maintenance and renewal requirements, so that the good quality tracks can run more trains per hour, longer operating hours and achieve a better punctuality. However, the constant budget and increasing operation restriction put more and more pressures to infrastructure manager. IM has no choice but focusing on costs when planning work possession time and deciding the closure of railway line at tactical planning level.

However, railway transports millions of passengers daily. Any closure of a railway lines on the maintenance and renewal purpose can delay a lot of passengers, and give the impacts to the whole society. The low cost maintenance and renewal plan is not always the best solution for passengers. In order to minimize the overall impacts, it is necessary to evaluate the alternative options from a larger scope, including the passenger loss into the overall costs to rank the proposals.

The article introduces a phase-based planning toolkit which integrating the passenger loss and direct costs into the comparison at planning stage. Passenger loss is estimated basing on the potential delay time values. The case study of S-Train stations shows the potential loss from passengers is one of the key costs impacting the railway closure decision. Especially for the busiest railway section, it even dominates the result of the overall proposals' ranking. It is therefore required to plan the railway closure time according to passenger loss. It could be a very hard decision for infrastructure manager because in some case the chosen solution might be the most expensive one for them.

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LIST OF ABBREVIATION

BDK	Banedanmark
CBR	Case-Based Reasoning (method)
CCT	Corrective Condition-based Tamping
CC-Zone	Constrained Construction Zone
CoO	Constrained Optimization
CPM	Critical Path Method
DKK	Danish kroner
DSS	Decision Support System
EcO	Economic Optimization
ERTMS	European Rail Traffic Management System
Fa	Fredericia
F-PBPA	Functional Phase-Based Planning Approach
HV	High Voltage
IM	Infrastructure Manager
IRISSYS	International Railway Inspection and Services System
LCC	Life Cycle Cost
LOB	Line Of Balance
LSM	Linear Scheduling Method
MCM	Minimal Cost Model
MILP	Mixed Integer Linear Programming
MTBF	Mean Time Before Failure
MTM	Minimal Tamping Model
M&R	Maintenance and Renewals
NPV	Net Present Value
NRC	New Recovery Constraints
Od	Odense
OR	Operations Research
PCT	Preventive Condition-based Tamping
PDSS	Phase-based Decision Support System
PO-PBPA	Process-Oriented Phase-Based Planning Approach
PSMS	Preventive Maintenance Scheduling Problem
PSP	Project Scheduling Problem
RAMS	Reliability, Availability, Maintainability and Safety
Rb	Rødby

RFB	Ringsted-Femern Banen
Rg	Ringsted
RPCBTSP	Railway Preventive Condition-Based Tamping Scheduling Problem
RPTSP	Railway Preventive Tamping Scheduling Problem
RSM	Repetitive Scheduling Method
RTPSP	Railway Track Possession Scheduling Problem
S&C	Switches and Crossings
SD	Standard Deviation
SP	Strategic Planning
TAM	Track Analysis Model (System)
TCC	Total Construction Cost
TeO	Technical Optimization
TOC	Train Operation Company
TQ	Track Quality
TS	Tamping Section
Vb	Vordingborg
VoT	Value of Time
YP	Yearly Planning